TO DEVELOP A CLEAN SMELTING PROCESS FOR HIGHLY ROASTED COPPER-NICKEL CALCINES AND TO IMPROVE METAL RECOVERY

PART A: THERMOGRAVIMETRIC - GAS CHROMATOGRAPHIC ANALYSIS OF SMELTING

Final Report
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TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY

ABSTRACT

1. INTRODUCTION 1

1.1 Background to Electric Furnace Smelting 1

1.2 Laboratory Study 2

2. EXPERIMENTAL METHOD 3

3. MATERIALS 4

4. TEST PROGRAM 6

5. PRESENTATION OF RESULTS 7

6. SERIES 1: NITROGEN ATMOSPHERE, NO LIME ADDITION 7

6.1 Lower Temperature Region (Up to 900°C) 9

6.1.1 Characteristic Features 9
6.1.2 Postulated Reactions 9

6.1.2.1 Low Temperature Reactions (<400°C) 9
6.1.2.2 Thermal Decomposition of Sulphides (450-700°C) 10
6.1.2.3 Sulphate Decomposition (700-830°C) 12
6.1.2.4 Solid State Sulphide-Oxide Reactions (400-900°C) 14
6.1.2.5 Solid State Coke-Oxide Reaction (300-800°C) 15

6.2 High Temperature Region (Above 900°C) 15

6.2.1 Characteristic Features 15
6.2.2 Postulated Reactions 16

6.2.2.1 Reduction Reactions 16
6.2.2.2 Effect of Degree of Roast 16
6.2.2.3 Effect of Coke Addition 18
6.2.2.4 Reduction Mechanisms 23
6.2.2.5 High Temperature SO_2 Producing Reactions 24

TABLE OF CONTENTS (cont'd)

Page

7. **SERIES 2: NITROGEN ATMOSPHERE, 0-15% LIME ADDITION** 27

7.1 Lime Alone: Modification of TGA Curves 27

7.2 Calcine-Lime Mixtures 27

7.2.1 Characteristic Features 27
7.2.2 Postulated Reactions 28

7.2.2.1 SO_2 and SO_3 Absorption Reactions 28
7.2.2.2 Reduction Reactions 29

8. **SERIES 3: AIR ATMOSPHERE** 30

8.1 Coke Alone 30

8.2 Calcine Tests in Air 32

8.2.1 Characteristic Features 32
8.2.2 Postulated Reactions 32

8.2.2.1 Low Temperature Reactions (<300°C) 32
8.2.2.2 Sulphate Formation (300-680°C) 33
8.2.2.3 Solid Sulphide-Air Reactions (350-900°C) 35
8.2.2.4 Coke-Air Reaction (400-1200°C) 36
8.2.2.5 Solid State Sulphide-Oxide Reactions 36
8.2.2.6 Sulphate Decomposition (700-830°C) 36
8.2.2.7 Reduction Reaction (850-1200°C) 37
8.2.2.8 High Temperature Air-Sulphide Reactions (1000-1200°C) 38

9. **CONCLUSIONS** 39

9.1 Summary of Results 39

9.2 Degree of Sulphur Elimination 42

9.3 Utilization of Coke 42

9.4 Lime Addition 43

TABLE OF CONTENTS (cont'd)

APPENDICES

APPENDIX 1 Graphical Results for Test Series 1: Nitrogen Atmosphere, No Lime

APPENDIX 2 Graphical Results for Test Series 2: Nitrogen Atmosphere, 0-15%, Lime Addition

APPENDIX 3 Graphical Results for Test Series 3: Air Atmosphere

REFERENCES

LIST OF TABLES

Table 1 Chemical Analysis of Calcines and Concentrate

Table 2 Test Conditions

Table 3 Schedule of Arrested TGA Tests

Table 4 Mineralogical and Chemical Data for Cu-Ni Concentrate

Table 5A Effect of Stoichiometry of Pyrrhotite on SO_2 Evolution

Table 5B Effect of Sulphur Content of Intermediate Solid Solution on SO_2 Evolution

Table 6 Thermal Stability of Metal Sulphates

Table 7 Equilibrium Products for Carbon-Sulphate Reactions

Table 8 Thermodynamic Data for Sulphide-Oxide Reactions

Table 9 Chemical Analyses of Products from Arrested TGA Tests: Effect of Temperature

Table 10 Chemical Composition of Metallics

Table 11 Peak CO/CO_2 Ratios

Table 12 Equilibrium Products for Reaction $FeS_2 + Fe_2O_3 + CaO + xC =$

Table 13 Equilibrium Products for Reaction $yFe_2(SO_4)_3 + C + CaO$

Table 14 Equilibrium Constants for Lime - Enhanced Reduction of Sulphides

Table 15 Equilibrium Products for Reaction $FeS + CaO + C =$

Table 16 Effect of % Coke on Sulphate Formation

Table 17 Effect of % Roast on Sulphate Formation

Table 18 Effect of Temperature on Sulphate Decomposition

Table 19 Terminal Weight Losses for Series 3: Adjusted for Coke Combustion

Table 20 Comparison of Terminal Weight Losses - Nitrogen and Air Atmospheres

LIST OF FIGURES

Fig. 1 Schematic Diagram of the Apparatus

Fig. 2 Trend Graphs for Series 1 Tests: Nitrogen Atmosphere, No Lime

Fig. 3 Metallic Saturation Boundaries in the (Ni + Cu)-Fe-S System

Fig. 4 The $FeO-Fe_2O_3-SiO_2$ System

Fig. 5 Fe-S-O Activity Diagram at 1200°C

Fig. 6 Crucible Cross Sections for Series 1 Tests

Fig. 7 Trend Graphs for Series 3 Tests: Air Atmosphere, No Lime

Fig. 8 Temperature Ranges for Reactions: Nitrogen Atmosphere

Fig. 9 Temperature Ranges for Reactions: Air Atmosphere

EXECUTIVE SUMMARY

The new Falconbridge Smelter Environmental Improvement Project was started up in 1978. The process circuit consists of slurry-fed fluid bed roasters for partial roasting of the nickel-copper concentrate, electric furnaces for smelting the calcine, and matte converters. The roaster gases supply sulphur dioxide to an acid plant while dilute sulphur dioxide streams from the electric furnaces and converters are vented to the atmosphere. The plant was originally designed for removal of 50% of the sulphur in the roasters; this has been increased to 55-60%. Increasing the degree of roast further would give an additional decrease in sulphur dioxide emissions by increasing the fraction converted to sulphuric acid.

When the degree of roast is increased, more heavily oxidized calcines and higher matte grades in the electric smelting furnace result and both are detrimental to smelter metal recoveries. The counter-measure is to smelt under more intensive reducing conditions by raising the reductant feedrate. Therefore, a clear understanding of the processes taking place in the charge to the electric furnace and the behaviour of coke in the reduction process is required in order to develop the proposed higher roast regime.

A thermogravimetric (TG) analyzer - gas chromatograph (GC) combination was used to examine the behaviour of electric furnace feed mixtures of calcine and coke. Because the smelting reactions involved gases to a large extent, the TG-GC combination was required for this investigation. The sample heating rate was selected to reflect the residence time in the smelting furnace. As the temperature increased, specific reactions that occurred were identified according to temperature of occurrence, quantity reacted, the rate of reaction, and the composition of the gaseous products. Additional samples were examined by arresting the process at various temperatures. The condensed phase composition was determined by chemical analysis and sections were examined metallographically and with electron-probe micro-analysis.

The behaviour of calcines roasted from 50 to 75% sulphur elimination were quantified under nitrogen and air. The effect of different levels of coke and lime additions on the smelting process were examined.

The data from this testwork, in conjunction with thermodynamic analysis, have been applied to determine the sequence of chemical reactions encountered in a unit of charge during its progress from the freeboard to the liquid slag. These are classified according to the temperature range of occurrence in Figure 8 (nitrogen atmosphere) and Figure 9 (air atmosphere). These figures constitute a graphic display of reactions within a vertical section of the charge layer in an electric smelting furnace. Heating by slag resistance in an electric smelting furnace establishes a temperature gradient, from approximately 500°C at the freeboard to 1230°C at the slag. The low temperature reactions occur partly in contact with ingress air to the furnace and Figure 9 is representative. The high temperature reactions occur at greater depth within the bed where the oxygen supply is limited both by the need for diffusion into the charge layer

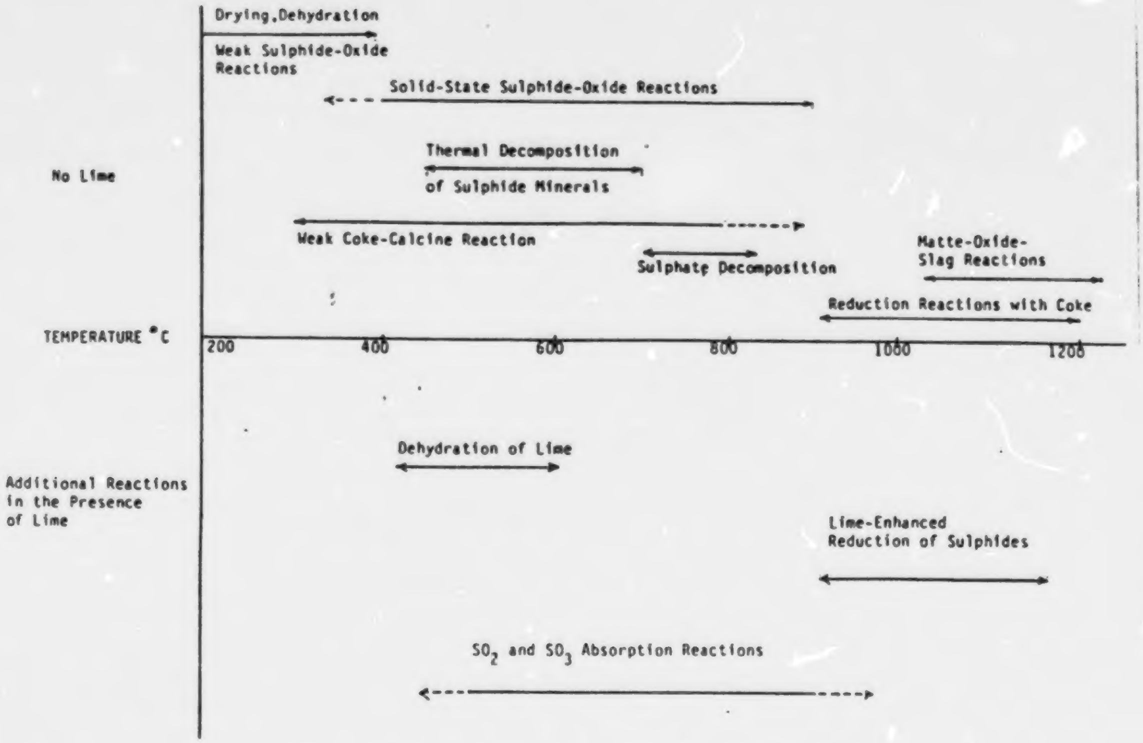
Drying,Dehydration
Weak Sulphide-Oxide Reactions
Solid-State Sulphide-Oxide Reactions
Thermal Decomposition of Sulphide Minerals
No Lime
Weak Coke-Calcine Reaction
Matte-Oxide-Slag Reactions
Sulphate Decomposition
Reduction Reactions with Coke
TEMPERATURE °C
200
400
600
800
1000
1200
Dehydration of Lime
Additional Reactions in the Presence of Lime
Lime-Enhanced Reduction of Sulphides
SO_2 and SO_3 Absorption Reactions

Fig. 8 Temperature Ranges for Reactions : Nitrogen Atmosphere

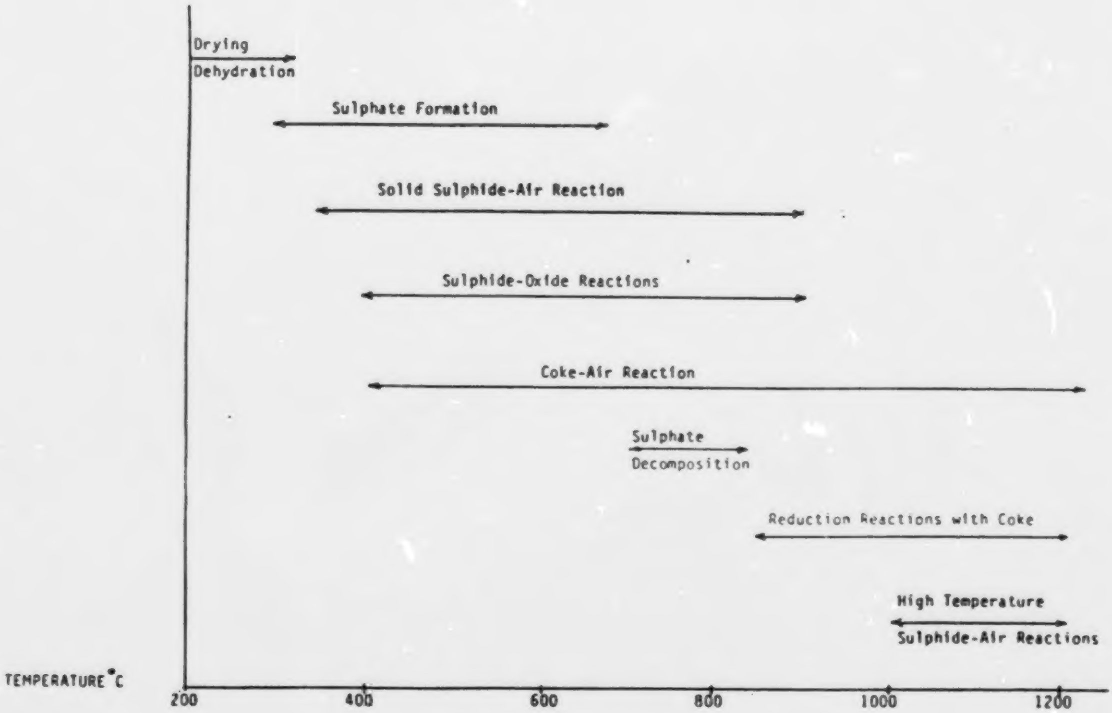
Drying
Dehydration
Sulphate Formation
Solid Sulphide-Air Reaction
Sulphide-Oxide Reactions
Coke-Air Reaction
Sulphate Decomposition
Reduction Reactions with Coke
High Temperature Sulphide-Air Reactions
TEMPERATURE °C
200
400
600
800
1000
1200

Fig. 9 Temperature Ranges for Reactions : Air Atmosphere

and the increasing reactivity of coke at higher temperatures. These reactions are represented in Figure 8.

Additional important aspects to smelting were determined and summarized in the following text.

A higher degree of roast at higher temperatures (a) produces a more inert, lower sulphide-bearing calcine; and (b) improves mineral decomposition to reduce the labile sulphur level. Therefore, an inverse relationship was observed between the volume of sulphur dioxide generated during smelting and the degree of sulphur elimination from calcine by prior roasting. Thus, sulphur emissions from the electric furnace are expected to decrease at higher degrees of roast.

Original sulphates in the calcine contributed directly to sulphur trioxide and sulphur dioxide formation during smelting by undergoing thermal decomposition. Therefore, control of sulphate formation during roasting is essential.

The air-sulphide reaction depends upon the diffusion of air into the charge. Thus, sulphur dioxide formation would be depressed by operating with a deeper calcine layer in the smelting furnace.

The mass of matte formed decreases as the degree of roast is raised because of the limited quantity of sulphur and the preferential distribution of oxidized iron to the slag. Thus, a smaller quantity of higher grade matte forms when highly roasted calcines are smelted. Concurrently, valuable metals (Co, Ni, Cu) are also partly oxidized to slag to necessitate the addition of more reductant.

Coke utilization in electric smelting is primarily in the matte-assisted reduction of oxides. These reactions are very rapid and are tolerant of different coke feeds. Reductant consumption within this regime is complete and rapid and progresses readily beyond the alloy precipitation boundary.

Substantial coke burnoff occurs through contact with ingress air at temperatures above 300°C. Direct coke combustion is disadvantageous because of diminished availability for metal oxide reduction and the creation of unacceptably high freeboard temperatures in the smelting furnace. Also, some unnecessary reduction of sulphates can occur.

The primary benefit of lime addition is the absorption of SO_2 evolved in the charge heating temperature range, up to 950°C. At higher temperatures, the reduction reactions may be enhanced by lime. At high degrees of roast of calcine such as 67%, the SO_2 capture is nearly complete at lime dosages from 5% to 15%. The stable sulphur-bearing compound under reducing conditions is CaS, though $CaSO_4$ may also exist.

RÉSUMÉ

C'est en 1978 que l'on a formulé le dernier Projet d'amélioration de l'environnement pour l'installation métallurgique de Falconbridge. Il s'agit d'une part de fours à lit fluidisé alimentés de boue, servant au grillage partiel des concentrés de nickel et de cuivre, et, d'autre part, de fours électriques effectuant la fusion des concentrés calcinés, ainsi que de convertisseurs de la matte qui en résulte. Les gaz émis au cours du premier grillage alimentent une usine de fabrication d'acide, tandis que le bioxyde de soufre ayant son origine dans les fours électriques et les convertisseurs s'échappe dans l'atmosphère ambiante. A l'origine, l'installation prévoyait l'élimination de 50% du soufre au niveau du premier grillage; ce chiffre a été amené depuis à 55-60%. Une deuxième augmentation de l'intensité de grillage réduirait davantage les émissions de bioxyde de soufre avec l'augmentation de la proportion convertie en acide sulfurique.

D'une intensification du grillage il résulte des concentrés calcinés plus oxydés et des mattes d'une teneur plus élevée en métal, ce qui, dans les deux cas, agit de façon défavorable sur le taux de récupération des métaux au cours du traitement. Afin de compenser ces désavantages, il serait souhaitable d'introduire des conditions plus intensives de réduction en augmentant la vitesse d'alimentation de l'agent réducteur. C'est pourquoi une compréhension de l'action qui se poursuit dans la charge du four électrique ainsi que du comportement du coke en ce qui concerne le processus de réduction est importante si l'on veut réaliser le régime de grillage plus intensif envisagé.

A cause de la prépondérance du rôle des gaz dans les réactions chimiques ayant lieu au cours de la fusion, il a fallu, pour les besoins de notre étude, avoir recours à une combinaison de thermogravimétrie et de chromatographie pour examiner le comportement des mélanges de concentrés calcinés et de coke destinés au four électrique. La vitesse de chauffage de l'échantillon a été choisi en fonction de la durée du traitement métallurgique. A mesure que la température a augmenté, les réactions ayant lieu ont été précisées selon la température à laquelle elles se produisaient, la quantité participant à la réaction, la vitesse de réaction et la composition des gaz en résultaient. D'autres échantillons ont été examinés en arrêtant le traitement à des températures données. La composition de la phase condensée a été déterminée au moyen d'analyses chimiques et diverses sections ont fait l'objet d'un examen métallographique et d'une analyse avec microsonde électronique.

Le comportement des concentrés calcinés ayant perdu au cours du grillage de 50 à 75% de leur contenu en soufre a été quantifié en présence d'azote et d'air respectivement. On a aussi examiné les effets sur le processus métallurgique en variant les additions de coke et de chaux.

Nous avons utilisé les données obtenues ainsi que le résultat de l'analyse thermodynamique afin de déterminer l'ordre des réactions chimiques qui se produisent au sein d'une charge donnée au cours de sa progression du franc-bord jusqu'à la scorie liquide. Nous classons ces réactions selon la gamme de températures où elles se produisent (figure 8, en présence d'azote; figure 9, atmosphère d'air). Les schémas représentent les réactions ayant lieu dans une section verticale de la couche de matières à fondre à l'intérieur d'un four électrique. Le chauffage obtenu en utilisant la résistance de la scorie d'un four électrique métallurgique établit un gradient de température allant de 500°C approximativement (au franc-bord) jusqu'à 1230°C (dans la scorie). Les réactions à basse température se réalisent partiellement au contact de l'air arrivant au four, la figure 9 étant typique. Les réactions à haute température se produisent en profondeur dans le lit du four où la quantité d'oxygène est restreinte à cause, d'une part, de la diffusion obligatoire de celui-ci dans la couche de la charge, et, d'autre part, de la plus grande réactivité du coke à des températures supérieures. (Voir Figure 8).

D'autres constatations importantes relatives à la fusion ont été faites; on les examinera dans les pages qui suivent.

Un grillage plus intensif à des températures plus élevées (a) produit une substance plus inerte et contenant moins de sulfure et (b) réduit le niveau de soufre labile en favorisant la décomposition minérale. Nous avons donc constaté l'existence d'un rapport inverse entre le volume de bioxyde de soufre produit au cours du traitement par fusion et le niveau d'élimination du soufre obtenu par le grillage antérieur. Par conséquent, il est prévisible que les émissions de soufre du four électrique vont baisser avec des intensités supérieures de grillage.

Les sulfates qui se trouvent à l'origine dans les concentrés calcinés au cours du grillage se sont décomposés dans les conditions thermiques de la fusion, contribuant ainsi directement à la formation, à ce stade du traitement, de trioxyde sulfurique et de bioxyde de soufre. Par conséquent, il est essentiel de surveiller de près la formation des sulfates au stade du grillage.

La réaction air-sulfure dépend de la diffusion d'air dans la charge. La formation de bioxyde de soufre se verrait donc réduite si l'on opérait dans une couche plus profonde de la charge.

La masse de matte produite diminue à mesure que l'on intensifie le grillage en raison du manque de soufre qui résulte et parce que la distribution du fer vers la scorie est favorisée. Donc, une quantité moindre de matte plus pure résulte de la fusion des calcinés ayant subi un grillage plus intense. Des métaux de valeur (Co, Ni, Cu) sont aussi partiellement oxydés pour former de la scorie, ce qui nécessite un dosage supplémentaire d'agent réducteur.

Dans le traitement des minerais au moyen du four électrique, le coke sert à la réduction des oxydes. Ces reactions se déroulent très rapidement et tolèrent diverses vitesses d'alimentation en coke. La consommation de l'agent réacteur suivant ce régime est complète et rapide, dépassant facilement le seuil de la précipitation des alliages.

A des températures supérieures à 300°C, il se produit la combustion de quantités considérables de coke au contact de l'air entrant dans le four. Cette combustion directe du coke a plusieurs inconvénients. D'abord, il en reste moins pour effectuer la réduction des oxydes des métaux; ensuite, il se crée des températures inacceptables au franc-bord; et, enfin, il peut en résulter une certaine réduction inutile des sulfates.

L'avantage principal des additions de chaux est l'absorption du SO_2 qui se manifeste aux températures atteintes par la charge, c'est à dire jusqu'à 950°C. A des températures plus élevées, les réactions réductrices peuvent être favorisées par la chaux. Avec des calcinés ayant subi un grillage suffisamment intense pour atteindre disons 67%, la capture de SO_2 est presque complète avec des doses de chaux de 5% à 15%. Le composé stable porteur de soufre dans les conditions de réduction est le CaS, bien que le $CaSO_4$ puisse également exister.

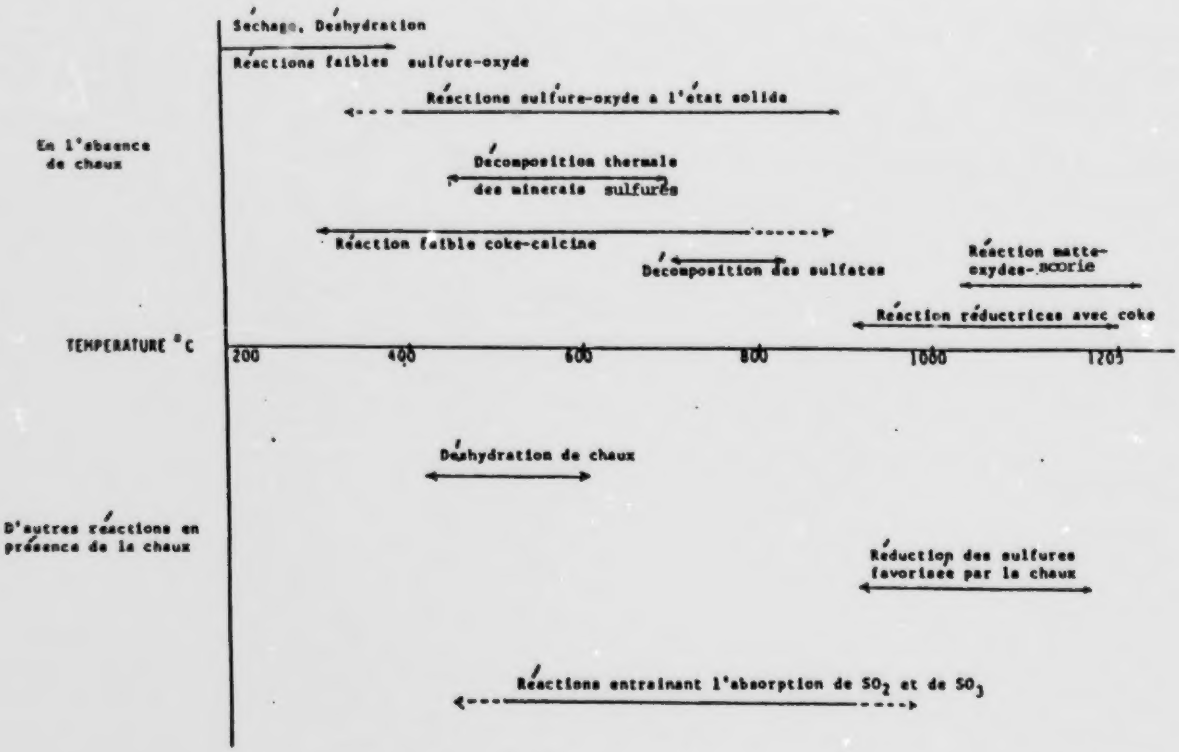

Fig. 8 Gamme de températures pour réaction: atmosphère d'azote

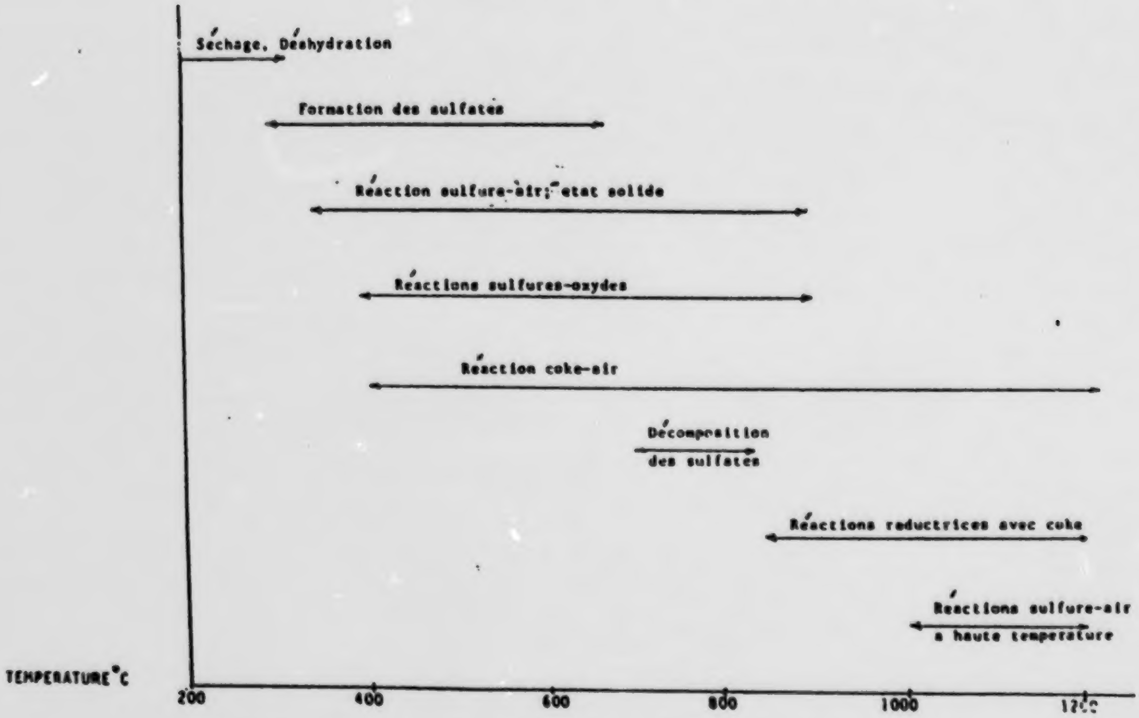

Fig. 9 Gamme de températures pour réactions: atmosphère d'air

ABSTRACT

A laboratory study was conducted to define the physical chemistry of reactions involved in the environmentally clean electric smelting of highly roasted copper-nickel concentrates.

Smelting behaviour was studied by a thermogravimetric-gas chromatographic technique in conjunction with chemical and micrographic analysis. The sequence and nature of reactions during the heating of calcines from 25 to 1250°C were identified by the temperature range and magnitude of weight changes and the characteristics of SO_2, CO, and CO_2 gas evolution. Four major variables examined were:

1) Gas atmosphere (nitrogen and air);

2) Degree of sulphur elimination from calcine (50-75%);

3) Coke addition (0-5%);

4) Lime addition (0-15%).

In the lower temperature range, (<900°C), substantial SO_2 evolution occurred from sulphide decomposition and oxidation reactions, and CO_2 from coke combustion in air. Above the fusion temperature, the dominant reaction was oxide reduction by coke in the presence of liquid matte, which acted as an oxygen transport medium.

Coke addition increases the extent and rate of reduction above 900°C, especially at levels above 3% of charge weight. Reduction is controlled by coke availability at dosages up to 5%.

Lime acts as an absorption medium for SO_2 and may participate in reduction reactions.

The significance of the experimental results is discussed in the context of electric smelting at high metal recoveries. Consideration is given to coke utilization, SO_2 release, and the implications of increasing the degree of roast of concentrate.

1.0 INTRODUCTION

A research program was undertaken to develop a clean smelting process for copper-nickel concentrate roasted to a high degree of sulphur elimination, with improved recovery of nickel and cobalt. Laboratory investigations were directed toward the definition of the metallurgical factors which are important in controlling metals recovery during reductive smelting. Part A of the study, entitled "Thermogravimetric-Gas Chromatographic Analysis of Smelting" is the subject of this report.

1.1 Background to Electric Furnace Smelting

The Falconbridge smelting process consists of fluid bed roasting of concentrates for partial sulphur elimination, electric smelting of calcine with coke, and Peirce Smith converting of matte. In the electric furnace, the smelting of calcine occurs in several stages which are delineated by the nature of the reactions involved and the temperature range of occurrence.

(a) Heating of the Charge (up to approx. 950°C)

During this period, freshly charged calcine and coke slowly proceed down into the furnace towards the liquid zone, rising in temperature from approximately 500°C at the calcine-freeboard surface to approximately 950°C at the fusion zone. As this material is heated, the reactions which occur are calcine sulphation, coke combustion, and roasting of sulphide minerals with freeboard air, as well as sulphide-oxide solid state reactions and sulphate decomposition. The oxygen balance of the furnace is affected by the sulphate formation-decomposition cycle and the consumption of some of the coke by reaction with ingress air. The quantity of oxygen presented to this stage is a function of the degree of roast of calcine. In addition, sulphur is lost from the charge as sulphur oxide gases are formed by several of the reactions.

(b) Coke Reduction and Sulphide Fusion (approx. 950 to 1150°C)

Within this temperature interval, matte formation occurs by fusion of sulphides in the calcine. The coke remaining after the charge heating period rapidly reduces iron oxides with the aid of the newly formed liquid matte, which acts as an oxygen transfer medium. The effectiveness of this mechanism influences the nickel and cobalt contents of the slag. The quantity and quality of coke added to the furnace charge affect the rate and extent of this reaction.

(c) Matte-slag Separation by Settling (approx. 1150 to 1250°C)

Within this temperature range, slag is formed by the reaction of silica flux and magnetite remaining in the calcine with iron and oxygen in matte. Matte-slag separation occurs and the matte droplets begin to settle down through the slag layer. Good phase separation is promoted by the formation of a low viscosity slag at relatively high Fe/SiO_2 ratios . However silica additions must be maintained in excess to flux the iron-rich recycled converter slag. Also, over-reduction of the calcine is necessary to produce metallized matte in the upper smelting region to reduce recycled converter slag. Therefore, the Fe/SiO_2 ratio of the slag which forms directly from the feed calcine is lowered further as iron oxide is reduced by coke in the fusion zone. The overall result is a fusion zone smelting system which consists of highly metallized matte and viscous, low Fe/SiO_2 ratio slag.

(d) Converter Slag Reduction (approx. 1200°C)

The converter slag returning to the electric furnace contains approximately 16% magnetite, and contributes a significant input of oxygen to smelting. It is believed that this slag preferentially flows to the matte-slag interface. Magnetite reduction must occur within this layer by reaction with the falling metallized matte droplets and with the bulk matte below.

The composition and quantity of the matte droplets is determined by the oxygen balance in the upper smelting regions.

(e) Matte Accumulation in the Hearth (approx. 1100°C)

Matte droplets, initially formed in the calcine layer, coalesce and accumulate in the furnace hearth after reacting with the original slag and the converter slag layer.

1.2 Laboratory Study

The investigations comprise of an examination of the initial stages of smelting, starting with the heating of the charge, then reduction by coke, fusion of sulphides, and slag formation. The purpose was to provide a sound understanding of the chemical processes which occur during the smelting of copper-nickel concentrate in the Falconbridge electric furnace, and to derive some insight into the mechanisms which may control or constrain the process result.

The study was designed to quantify the description of the important first steps in smelting in terms of the sequence of reactions, the temperature range, and the gases evolved.

Key variables were designated for this part of the research, as follows:

(a) Degree of Sulphur Elimination from Calcine during Roasting, Prior to Smelting

The current value at Falconbridge is 60%, but an increase to levels as high as 75% would ameliorate the control of sulphur distribution at the smelter. However, this advantage must be balanced against the possibility of increased metal loss to slag. For this work, degrees of roast from 50 to 75% were studied.

(b) Coke Addition to the Smelting Charge

Coke is presently added to the smelter feed at the rate of 4% on concentrate. The nature of the participation of coke in smelting reactions must be related to the efficiency of reduction of highly roasted calcines. Coke rates from 0 to 5% of charge were used in the experiments.

(c) Lime Addition to the Smelting Charge

Sulphur dioxide evolved from the calcine during electric furnace smelting is not captured. Lime was considered as a potential in situ getter, and was added at rates of 0 to 15% of charge.

The analysis of the effects of changes to these variables serves to provide a basis for new approaches towards the improvement of the reduction smelting process.

2.0 EXPERIMENTAL METHOD

Since many smelting reactions involve the transfer of sulphur and oxygen through a gas atmosphere, an experimental method was developed to monitor changes in both the condensed and gas phases. The behaviour of calcine mixtures was studied during heating to 1250°C by a thermogravimetric analyzer (TGA) - gas chromatograph (GC) combination. This method provides a correlation of weight changes and gas compositions with temperature. Chemical reactions may be identified according to the temperature range of occurrence, reaction rate, and extent.

A schematic diagram of the apparatus is shown in Fig. 1.

For each test a sample of calcine, weighing approximately 5 to 8.5 grams, was placed in a crucible which was suspended from an electronic microbalance. This device provided a continuous record of weight changes. The crucible was enclosed in a sealed Vycor reaction tube which was continuously flushed with nitrogen or air at 900 ml/min. to maintain a controlled atmosphere. The tube was heated in a Kanthal-wound resistance furnace operated by a programmable temperature controller. A heating rate of 5°C/minute was selected to simulate the full-scale smelting furnace.

Gases evolved from the charge were sampled periodically by a syringe, through a 1 mm diameter silica tube located adjacent to the crucible. The gases were analyzed for CO, CO_2, and SO_2 content by a Hewlett-Packard 5880A gas chromatograph equipped with a Poropak-Mole Sieve series column.

As the TGA-GC method alone does not positively identify chemical reactions, other techniques were employed to obtain more comprehensive data in specific cases. In some tests the heating was arrested at different temperatures and the samples were examined in several ways, as follows:

1. visual or optical examination of sections
2. chemical analysis of products
3. micrographic and electron microprobe analysis of polished sections

These provided chemical and mineralogical data to link the TGA-GC outputs with reaction mechanisms.

3.0 MATERIALS

Calcines were roasted in a fluidized bed roaster to four different degrees of sulphur elimination: 50%, 60%, 67%, and 75%. The chemical analyses of these calcines, as well as the nickel-copper concentrate from which they were prepared, are shown in Table I. The composition of the coke is also provided.

The 50% roasted calcine was silica-deficient, and quartz flux was added to adjust the iron:silica ratio in those charges. No flux additions were made to the other calcines.

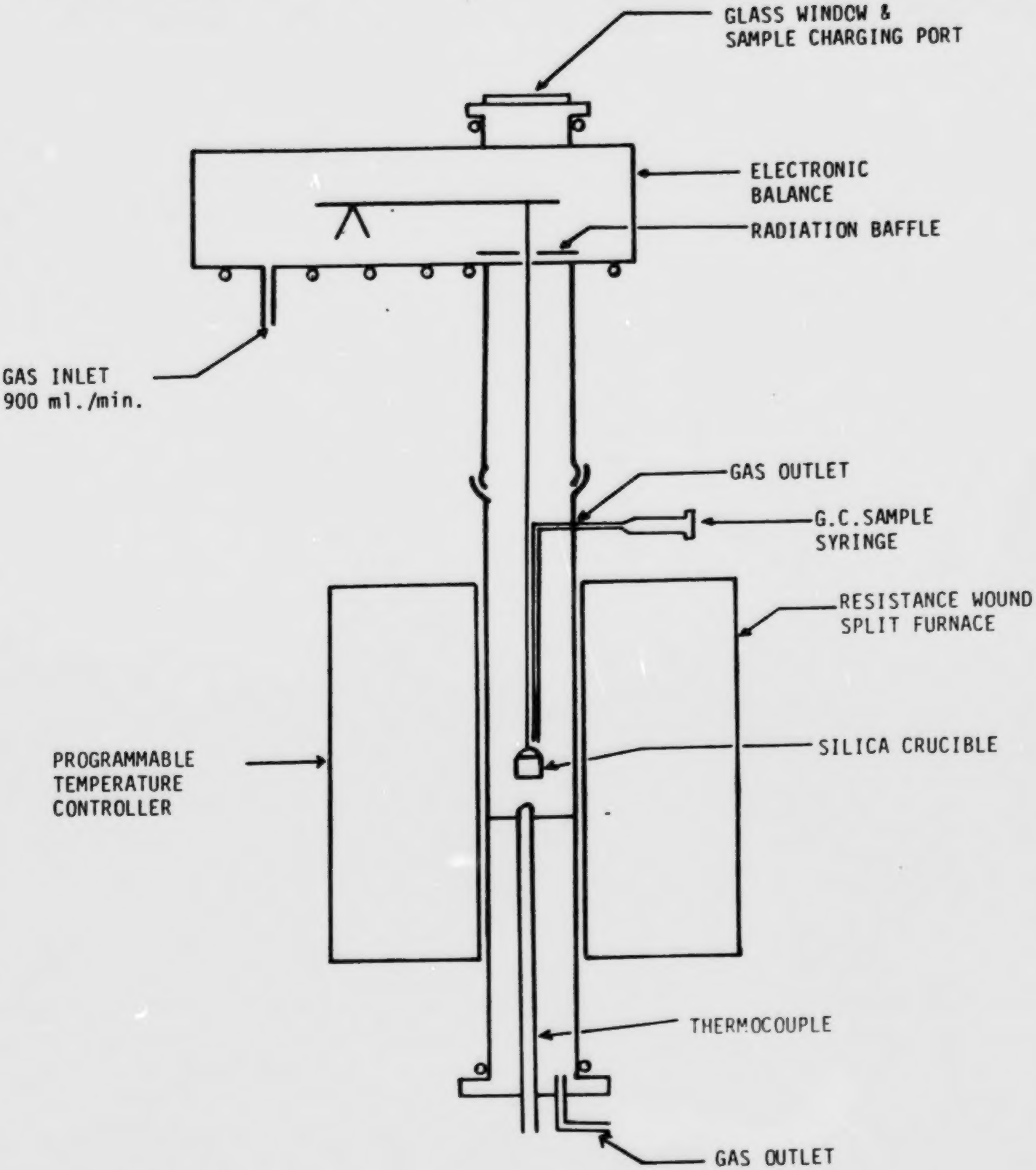
GLASS WINDOW & SAMPLE CHARGING PORT
ELECTRONIC BALANCE
RADIATION BAFFLE
GAS INLET 900 ml./min.
GAS OUTLET
G.C.SAMPLE SYRINGE
RESISTANCE WOUND SPLIT FURNACE
SILICA CRUCIBLE
PROGRAMMABLE TEMPERATURE CONTROLLER
THERMOCOUPLE
GAS OUTLET

Fig. 1 Schematic Diagram of the Apparatus

TABLE 1: CHEMICAL ANALYSIS OF CALCINES AND CONCENTRATE

CALCINE

Sample No.	% Roast	Roasting Temp. (°C)	Ni	Cu	Co	Fe	S	SiO_2	SO_4	Fe_3O_4	Fe_2O_3	Al_2O_3	CaO
B4494	50	620	6.6	4.7	0.27	38	16.3	12.0	0.55	25.7	7.7	2.2	1.26
B5701	60.6	680	6.3	6.4	0.25	39	11.8	16.0	0.20	23.1	17.0		
B5705	67.5	680	5.9	6.1	0.24	36.5	9.2	19.5	0.37	15.7	21.0		
B5703	75.5	750	6.2	6.2	0.25	39	7.2	17.0	0.22	27.0	21.3		

CONCENTRATE (Typical Values %)

Ni	6.0-6.6	Fe	41-43
Cu	4.9-6.6	S	30.2-31.6
Co	0.25	SiO_2	5.9-7.8

COKE (Imperial Oil Fluid Bed)

Fixed C	97.2
S	3.8
Volatiles	2.4
Ash	0.38

4.0 TEST PROGRAM

Three series of tests were conducted under the conditions given in Table 2.

TABLE 2: TEST CONDITIONS

Series	Gas Atmosphere	% Coke	% Roast	% Lime
1	Nitrogen	0,1,3,5	50,60,67,75	0
2	Nitrogen	5	60,67	0,5,10,15
3	Air	0,1,3,5	50,60,67,75	0

In addition, lime only was tested in nitrogen and coke only was tested in both nitrogen and air.

The two different gas covers were applied in order to simulate the limiting conditions which exist during the smelting of a unit of charge. At the top of the charge bank, heating occurs in an oxygen-rich environment. Later, the unit of charge is substantially separated from the air, and the local atmosphere is determined by chemical reactions and rates of gas diffusion.

Separate runs were made for the arrested TGA tests, according to the schedule given in Table 3.

TABLE 3: SCHEDULE OF ARRESTED TGA TESTS

Purpose of Test	Gas Cover	% Coke	% Roast of Calcine	Temp. °C	Analysis Method
Effect of temp. on reaction mechanism	N_2	5	67	600-1250	Chemical & Micrographic
Effect of % roast on sulphate formation	Air	0	50-75	600	Chemical
Effect of % coke on sulphate formation	Air	0-5	67	600	Chemical
Effect of temp. on sulphate formation	Air	3	60	600-800	Chemical

5.0 PRESENTATION OF RESULTS

Results are reported and discussed in separate sections corresponding to the three main series of tests. Detailed results from the TGA-GC outputs are given in Appendices 1 to 3. These are in the form of graphs of weight change as a function of temperature, along with the corresponding volume % SO_2, CO, and CO_2 in the gas. To assist in discerning the effects of coke addition and degree of roast, these are plotted in two formats:

Fixed % roast; parameter = % coke

Fixed % coke; parameter = % roast

For tests carried out without carbon addition, no CO or CO_2 peaks were recorded. For certain tests which indicate a weight loss some of the gas analysis tracings are missing and were not obtained.

The large number of graphs require close inspection to yield complete information about the smelting process. For convenience, the important results within each test series are illustrated by an annotated TGA-GC graph selected from the Appendices and included within sections 6 and 8 of this report. Also given in these sections are the chemical analyses for arrested TGA tests and photographs of the crucible cross sections at the end of each run, as appropriate.

At the beginning of each section, the major phenomenological trends in weight change and gas evolution characteristics are described. Following this, the reactions which match the data are identified and the effects of the major variables are considered.

6.0 NITROGEN ATMOSPHERE, NO LIME

Complete data in graphical form are available in Appendix 1. One example of the data curves has been reproduced in the present section to form the basis for analysis and discussion of trends. This is Figure 2, "Trend Graphs for Series 1 Tests: Nitrogen Atmosphere, No Lime".

The data for a 60% roasted calcine are annotated to show qualitatively the effects of degree of roast and coke dosage on the TGA-GC response.

The graphs show that calcine charges heated under nitrogen lost weight at a moderate, nearly constant rate below 900°C, then reacted much more rapidly from 900 to 1250°C. For consideration of reaction mechanisms, these two regions are examined separately.

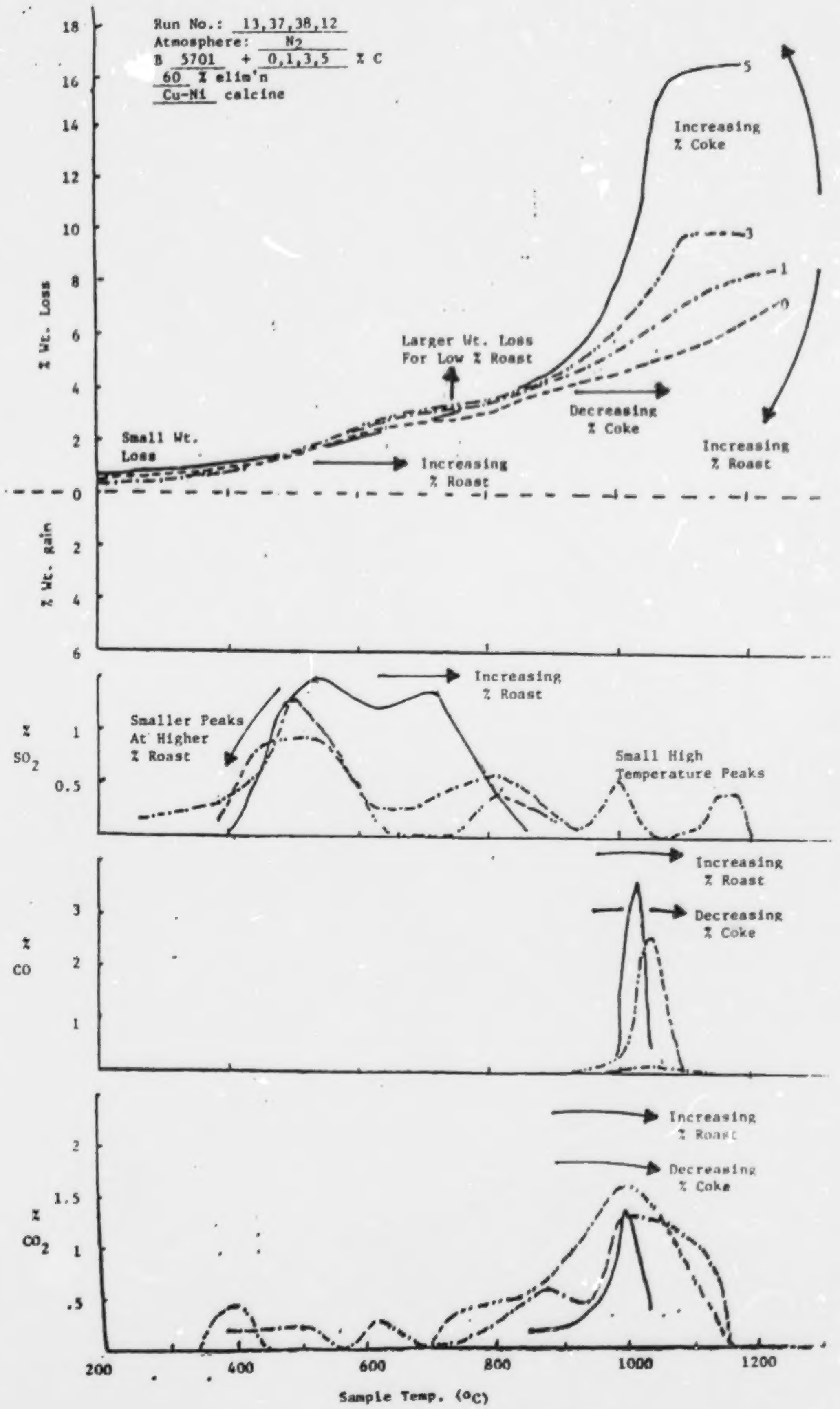

Fig. 2 Trend Graphs for Series 1 Tests: Nitrogen Atmosphere, No Lime

6.1 Lower Temperature Region (up to 900°C)

6.1.1 Characteristic Features

(a) Weight Changes

Up to 400°C, weight losses were small (<1%), with a low rate of change. Much of the weight loss already occurred at 200°C. There is a marked increase in change at approximately 400-480°C for all samples, followed by nearly constant loss to 900°C. The loss is greater for lower % roast, but is independent of coke addition. A small inflection occurs at 650-700°C for tests at low % roast. The point of initiation of more rapid weight loss shifts to higher temperatures as the % roast increases (eg. from 420 to 470°C as % roast changes from 50 to 75%).

(b) SO_2 Evolution

Some SO_2 is produced over the entire temperature range, but major peaks appear only at 500-600°C and 800-850°C. The amount of SO_2 generated (or peak height) is lower for more highly roasted calcines, and the first peak shifts to slightly higher temperatures at higher % roast.

(c) CO/CO_2 Evolution

Low level CO_2 evolution occurs starting at 400°C, but this cannot be correlated with coke addition or degree of roast. More rapid CO_2 evolution commences near 800°C, and in some cases, a distinct peak occurs here.

6.1.2 Postulated Reactions

6.1.2.1. Low Temperature Reactions (<400°C)

The three types of reaction which occur in this region are:

- elimination of residual free moisture;
- dehydration of chemically bound water;
- weak solid state sulphide-oxide reactions or thermal decomposition of sulphides.

The occurrence of some weight loss below 200°C for most samples indicates that there is removal of small amounts of free water.

Further weight changes in the temperature range 200 to 400°C are caused by the loss of chemically combined water. As shown in Table I, the calcines contain 0.2 to 0.55% of sulphur as metal sulphates which may be hydrated. Decomposition of hydrates with water evolution typically occurs in this temperature range; eg. $CuSO_4.5H_2O$ decomposes at 250°C. The calculated weight lossses for the decomposition of pentahydrates of iron and nickel sulphates in the calcine are in the range 0.5 to 1.5%. These values correspond well with the thermogravimetric data.

The presence of some SO_2 in the offgas at temperatures below 400°C indicates that some of the reactions which are important at higher temperatures have commenced, but are weak.

6.1.2.2. Thermal Decomposition of Sulphides (450-700°C)

Bulk copper-nickel concentrate consists of sulphide minerals plus siliceous gangue. A typical mineralogical analysis of concentrate and chemical analysis of constituent sulphide minerals is given in Table 4, "Mineralogical and Chemical Data for Cu-Ni Concentrate".

TABLE 4: MINERALOGICAL AND CHEMICAL DATA FOR Cu-Ni CONCENTRATE

(A) MINERAL TYPES

Mineral	Weight Percent
Pyrrhotite	42
Chalcopyrite	15
Pentlandite	22
Gangue	Balance

(B) CHEMICAL ANALYSIS

Mineral	Wt. %					Formula
	Fe	Ni	Co	Cu	S	
Pyrrhotite	58.4	0.59	0.08	0.08	39.5	$Fe_{0 \cdot 85}S$
Chalcopyrite	30.4	-	-	34.6	34.9	$CuFeS_2$
Pentlandite	29.6	36.0	1.4	0.04	33.0	$(Ni,Fe,Co)_{9 \cdot 0}S_8$

During partial roasting of concentrate, some alteration of sulphides occurs. However, the flying bed roasting method employed at Falconbridge allows only a very brief residence time within the reactor, such that thermal decomposition is incomplete. Micrographic analysis of arrested TGA products heated to 600°C revealed the presence of lightly altered chalcopyrite, pyrrhotite, and pentlandite minerals. The partly roasted sulphide particles in the calcine are surrounded by iron oxides and sulphates. This indicates a largely topochemical reaction which results in the formation of a clear interface between the original reactants and the products.

Upon further heating in the temperature range 450 to 700°C, some of the residual sulphide minerals in the calcine become thermally unstable. The calculated molecular formulas for minerals in Falconbridge concentrate, given in Table 4, provide a good indication of the tendency for thermal decomposition.

For iron sulphides, the labile sulphur is readily evolved at atomic Fe/S ratios less than unity. On this basis, the behaviour of the three sulphide minerals may be described as follows:

(1) Pyrrhotite

Pyrrhotite may be considered as a sulphur-rich iron sulphide $Fe_{1-y}S$, where the value of y = 0.15 for Falconbridge concentrate. The PS_2 values given in Table 5A are applicable to the decomposition of S-rich pyrrhotite. Sulphur vapour will react with oxides to produce SO_2 as follows:

$$6Fe_2O_3 + 1/2\ S_2 = 4Fe_3O_4 + SO_2$$

Table 5A gives the equilibrium value for PS_2 during pyrrhotite decomposition along with the corresponding PSO_2 for the reaction with Fe_2O_3.

TABLE 5A: EFFECT OF STOICHIOMETRY OF PYRRHOTITE ON SO_2 EVOLUTION

T (°C)		Atomic % Fe				
		46	47	48	49	50
527	log PS_2	-3.8	-5	-7	-9.5	-14
	log PSO_2	0.56	-0.04	-1.05	-2.3	-4.5
627	log PS_2	-1.8	-3.4	-5.2	-7.8	-11.8
	log PSO_2	2.5	1.7	0.8	-1.47	-2.5

PS_2, PSO_2 are expressed in bar

(2) Chalcopyrite

The maximum thermal stability temperature of chalcopyrite is 557°C, above which complete decomposition occurs according to the following equation:

$$CuFeS_2 = iss + FeS_2$$

After the small amount of pyrite has decomposed, the PS_2 values depend upon the stoichiometry of the iss. The effect of increasing sulphur deficiency is shown in Table 5B along with the PSO_2 values arising from the reaction with Fe_2O_3.

TABLE 5B: EFFECT OF SULPHUR CONTENT OF INTERMEDIATE SOLID SOLUTION ON SO_2 EVOLUTION

	Atomic % S in iss		
T = 627°C	48	47	46
log PS_2	-2.9	-4.6	-6.5
log PSO_2	1.98	1.13	0.18

(3) Pentlandite

Pentlandite is metal rich and relatively stable. The variable stoichiometry of natural pentlandites precludes exact thermodynamic analysis. At 600°C, the Ps_2 values over FeS-Fe and $NiS\text{-}Ni_{3-x}S$ approximate 10^{-13} and 10^{-7}atm. respectively ([5]). These are quite low compared with the values for pyrrhotite and chalcopyrite.

The thermodynamic data of Tables 5A and 5B show that significantly high PSO_2 values are available from the S_2-iron oxide reaction within a narrow temperature range. This is consistent with the observed SO_2 peaks at 450-650°C, as well as the trend towards diminishing SO_2 evolution for more highly roasted calcines.

The principal constraint on gas formation from thermal decomposition is the mass of mineral in the calcine, because the activity of sulphur drops markedly as the sulphur/metal ratio decreases. Thus, thermal decomposition is restricted, but still is sufficient to contribute to the rapid evolution of SO_2.

This mechanism is consistent with the trend towards a slower, weaker reaction as the quantity of sulphide minerals is diminished through increased degree of roast. With the greater abundance of sulphides in less roasted calcines, there is a larger weight loss and a correspondingly larger SO_2 peak. Typically, at 650-700°C, there is an inflection in the weight loss curve. This may be related to the disappearance of pyrite. At higher degrees of roast, the inflection is weak or absent. In these cases, the total weight change is quite small and the relative importance of the solid state sulphide-oxide reactions is greater; both these factors suppress the appearance of a distinct inflection.

Coke does not participate in these reactions and causes no significant differences in SO_2 evolution or weight loss behaviour.

6.1.2.3. Sulphate Decomposition (700-830°C)

The strong evolution of SO_2 at approximately 800°C is caused by the decomposition of metal sulphates in the calcine. Based upon the chemical analysis given in Table I, the calcine product from roasting contains 1 to 2.5% of metal sulphates. A micrographic analysis of a sample arrested at 900°C confirmed the disappearance of sulphates which were present at 600°C. Iron sulphates were most evident, as may be expected from the abundance of iron in the concentrate.

The breakdown of sulphates may occur by two different mechanisms, thermal decomposition and reduction by carbon.

(1) Thermal Decomposition

The thermal stability of metal sulphates with respect to their oxides decreases as the temperature is raised. Relative stabilities of copper, nickel, and iron sulphates can be expressed in terms of their equilibrium decomposition pressures, as given in Table 6.

TABLE 6: THERMAL STABILITY OF METAL SULPHATES

Reaction	*Vapour Pressure (atm) at Temperature (°C)		
	627°C	727°C	827°C
$Fe_2(SO_4)_3/Fe_2O_3$	0.079	1.0	7.9
$CuSO_4/CuO.CuSO_4$	0.011	0.17	1.55
$NiSO_4/NiO$	1.2×10^{-3}	0.027	0.33

*Vapour Pressure = $PSO_2 + PSO_3 + PO_2$

Ferric sulphate is the least stable compound; substantial decomposition would commence at 727°C, where the vapour pressure reaches 1 atm. At temperatures above 800°C, all of these sulphates decompose by reactions of the type $Fe_2(SO_4)_3 = Fe_2O_3 + 3SO_3$.

(2) Reduction by Carbon

Metal sulphates may also be reduced by solid carbon, with the evolution of SO_2 and CO_2. Equilibrium calculations for the reactions of carbon with $CuSO_4$ and $Fe_2(SO_4)_3$ were made by use of the FACT* computer system, with the results shown in Table 7.

TABLE 7: EQUILIBRIUM PRODUCTS FOR CARBON-SULPHATE REACTIONS

Reaction	Temperature (°C)	Stable Compounds
$CuSO_4 + C$	600 and 700	CO_2, SO_2, Cu_2S, Cu_2O,
	750 and 800	CO_2, SO_2, Cu
$Fe_2(SO_4)_3 + C$	527 and 627	CO_2, SO_2, Fe_2O_3, $Fe_2(SO_4)_3$
	727	CO_2, SO_2, SO_3, O_2, Fe_2O_3

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*Facility for the Analysis of Chemical Thermodynamics. Centre for Research into Computational Thermochemistry, Ecole Polytechnique de Montreal.

The thermodynamic study shows that the reduction of sulphates by carbon can occur at temperatures lower than those associated with their thermal decomposition. However, the kinetics of solid state reactions are likely to be slower than thermal decomposition reactions which require only the outward diffusion of product gases to proceed rapidly. The appearance of small CO_2 peaks in the range 600 to 800°C is associated with the reduction of either sulphates or oxides. There is evidence from the micrographic study that some sulphides were formed from the decomposition of sulphates at high coke dosages (5%).

There is little effect of the carbon addition on the TGA data near 800°C, except for the more rapid increase in weight loss at 5% coke.

The major cause of weight loss is SO_2 evolution. Carbon reduction of $CuSO_4$ produces an equal number of moles of CO_2 and SO_2, but little CO_2 was detected. Although both mechanisms of sulphate reaction are probably operative, thermal decomposition is dominant.

6.1.2.4 Solid State Sulphide - Oxide Reactions (400-900°C)

In the absence of an oxidizing atmosphere, the continuation of SO_2 evolution over a wide temperature range arises from solid state reactions of the type:

$$Me_2S + 6MeO = 4Me_2O + SO_2$$

This mechanism operates steadily, producing a background level of SO_2, rather than strong peaks at certain temperatures.

In partially roasted calcines, the concentration of both the oxide and sulphide reactants is high. Reactions with many sulphides and oxides are possible, but the high relative abundance of iron compounds in the calcine indicates that reactions which involve hematite, magnetite, and iron sulphide are most important. In Table 8, the calculated SO_2 pressures arising from several solid state reactions are shown. The PSO_2 values are sufficiently high for rapid evolution and confirm the favourable thermodynamic conditions for these reactions to proceed.

TABLE 8: THERMODYNAMIC DATA FOR SULPHIDE-OXIDE REACTIONS

	PSO_2 (atm)	
	423°C	623°C
$FeS+10Fe_2O_3 = 7Fe_3O_4+SO_2$	1.29	1.3×10^4
$Cu_2S+9Fe_2O_3 = Cu_2O+6Fe_3O_4+SO_2$	7.5×10^{-10}	2.9×10^{-4}
$Ni_3S_2+21Fe_2O_3 = 3NiO+14Fe_3O_4+2SO_2$	9.9×10^{-4}	107

The equations written in Table 8, represent overall reactions, and not necessarily the actual reaction path.

Rates of reaction are controlled by the availability of sulphide and oxide reactants in close proximity. During roasting, prior to smelting, the iron-nickel-copper sulphide mineral particles are partially oxidized on the outer surfaces, or topochemically. During the heating stage of smelting these particles may fracture or spall because of SO_2 evolution. Additionally, there is solid product formation at the oxide-sulphide interfaces. The SO_2 gas generated by solid state reactions must then diffuse through the calcine barrier layer to the surface. As a result of the kinetic factors, there is a sustained, moderate level of SO_2 evolution up to approximately 900°C, at which point high temperature reactions commence strongly.

6.1.2.5 Solid State Coke-Oxide Reactions (300-800°C)

Low level CO_2 evolution was noted at temperatures from 300 to 700°C, indicating the participation of coke in oxide reduction. In the absence of oxygen in the atmosphere only solid state coke-calcine reactions can occur. These are too weak to display consistent trends with coke dosage or oxide content of the calcine. Micrographic examination of arrested TGA samples confirm that coke particles are completely unaltered at 600°C, and are largely unreacted at 1000°C. At approximately 800°C stronger CO_2 evolution occurs, first through carbon reduction of metal sulphates, and then through high temperature reactions.

6.2 High Temperature Region (Above 900°c)

6.2.1 Characteristic Features

(1) Weight Changes

A very rapid increase in weight loss occurs near 950°C; it is a strong function of coke addition, but nearly independent of degree of roast. The initial temperature for this phenomenon decreases at higher coke additions, from about 900°C for samples with 5% coke to above 1000°C for those with no coke. It is also delayed at higher % roast.

(2) SO_2 Evolution

The evolution of SO_2 at temperatures between 950 and 1200°C is characteristic of samples with low coke addition (0 and 1%). Peaks are found at approximately 1000°C and 1150°C, but lower level SO_2 generation does occur throughout the temperature range. The quantity of SO_2 is greater at lower % roast, and decreases as more coke is added to the charge.

(3) CO/CO_2 Evolution

Strong CO and CO_2 evolution occurs from 900 to 1200°C for samples which contain coke. Peaks are centered around 1000-1100°C, and occur earlier for larger coke additions. Peak positions shift to higher temperatures as % roast increases. The maximum peak $CO:CO_2$ ratios are a function of coke addition, and increase markedly as the coke rate changes from 3% to 5%.

6.2.2 Postulated Reactions

6.2.2.1 Reduction Reactions

The high temperature region of the tests conducted under nitrogen corresponds most closely to the actual smelting stage in the electric furnace. During the heating of charge from about 900°C to 1250°C several important processes occur, as follows:

1. sulphide fusion to form liquid matte
2. reduction of oxides, mainly by coke via dissolution in matte
3. fusion of flux, gangue and oxides to form slag
4. separation of matte and slag phases

The compositions of matte and primary slag are determined by inputs or mass constraints and thermodynamic conditions, chiefly the oxygen potential of the system. These are substantially set by the two variables which were studied during the TGA-GC testwork:

1. degree of roast, which establishes the oxygen and sulphur input to smelting

2. coke addition, which provides a capacity for oxygen removal from the charge.

The phenomena associated with changes to these two variables are now considered.

6.2.2.2 Effect of Degree of Roast

The roasting of sulphide concentrates results in the simultaneous removal of sulphur as SO_2 and the addition of oxygen to the calcine as Fe_3O_4, Fe_2O_3, NiO and other oxides. Sulphur removal from the charge induces a change in the overall matte composition towards the metal solubility limits. This trend may be traced through Figure 3, which shows the estimated metallic saturation boundaries in the (Ni + Cu)-Fe-S system. At high degrees of roast, as employed by Falconbridge, sulphur availability is limited to the extent that metal precipitation occurs. Alloy and liquid matte compositions vary along the endpoints of the liquidus tie lines in the ternary diagram.

Increased sulphur removal through roasting causes several changes to the matte phase:

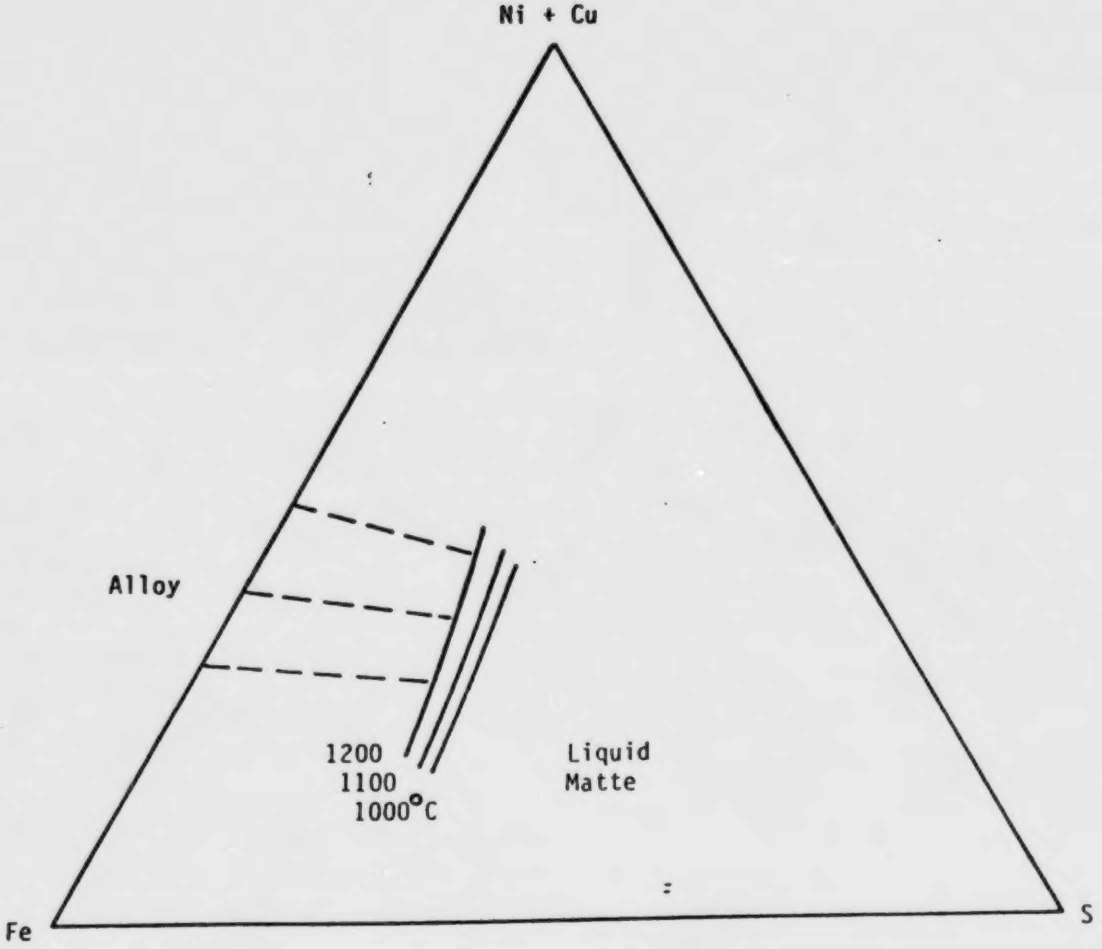

Ni + Cu
Alloy
1200
1100
1000°C
Liquid
Matte
Fe
S

Fig. 3 Estimated Metallic Saturation Boundaries in the (Ni + Cu)-Fe-S System

1. the composition of metallics shifts towards a higher $\frac{Ni + Cu}{Fe}$ ratio
2. the mass ratio of metallics to liquid matte increases
3. the mass of matte decreases

The influence of sulphur content in calcine is evident in Figure 6, which contains photographs of sections of crucibles taken after reaction to 1250°C. As the degree of roast rises from 50 to 75%, the volume of the matte phase clearly diminishes. This trend is particularly evident at low coke dosages because the dilution of matte with iron-rich metallics from carbon reduction of oxides is relatively small.

Along with the increase in the fraction of metallics in matte at higher degrees of roast, there is a corresponding increase in the overall matte grade, %(Cu + Ni + Co). The relative enrichment of metallics in Cu + Ni + Co is consistent with a higher oxygen potential in the system. However, the higher matte grade and oxygen potential are conditions which promote greater losses of Cu, Ni, and Co to slag through increased metal solubility and primary slag burden. Since the rationale for operation with higher degrees of roast is control of sulphur distribution in the smelter, reductant addition to the electric furnace is essential.

Sulphide availability also affects the initiation temperature of the rapid weight loss period. Weight losses in the high temperature region are caused by only the following two types of reactions:

1. reduction of solid oxides by coke via FeO dissolution in matte, forming CO and CO_2
2. oxide reactions with liquid matte, with SO_2 evolution; these reactions are much weaker than carbon reduction

In both cases the quantity of residual sulphides available for matte formation influences the contact surface area between matte, oxide, and coke (if present).

6.2.2.3 Effect of Coke Addition

In the absence of carbon, little weight change occurs above 950°C at all degrees of roast. Matte fusion and slag formation proceed but reduction can only occur by the relatively weak reactions with FeS, which are discussed later.

With the addition of coke the TGA curves are affected in two ways:

1. weight loss due to oxygen removed from the charge
2. weight loss due to the loss of coke itself

Micrographic examinations show that the coke is completely consumed even at the 5% addition level. Thus, weight losses in Figure 2 are considerably magnified by the mass of coke. If adjustment is made for this factor, then the high temperature curves are compressed closer, but with the same relative positions which correspond to the relative amounts of oxygen reduced from the charge.

The addition of coke to the charge causes a decrease in the oxygen potential of the system and provides a reductant for ferric iron. As a consequence the matte becomes more metallized by iron. On the (Ni+Cu)-Fe-S phase diagram in Figure 3, the addition of coke at any degree of roast corresponds to a shift in the overall matte composition towards the iron corner. For highly roasted calcines the matte becomes metal saturated, and a further effect is the increased mass of metallics compared with liquid matte as the reduction continues. Both matte grade and % sulphur content decrease as the dilution of matte by iron causes an increase in the total mass of matte. In Figure 6 the crucible cross-sections at the end of the tests show that there is an increase in the volume of matte (sulphide plus metallics) as the coke dosage rises from 0 to 5%. This is most evident at high degrees of roast because the quantity of metal sulphide is restricted by sulphur availability.

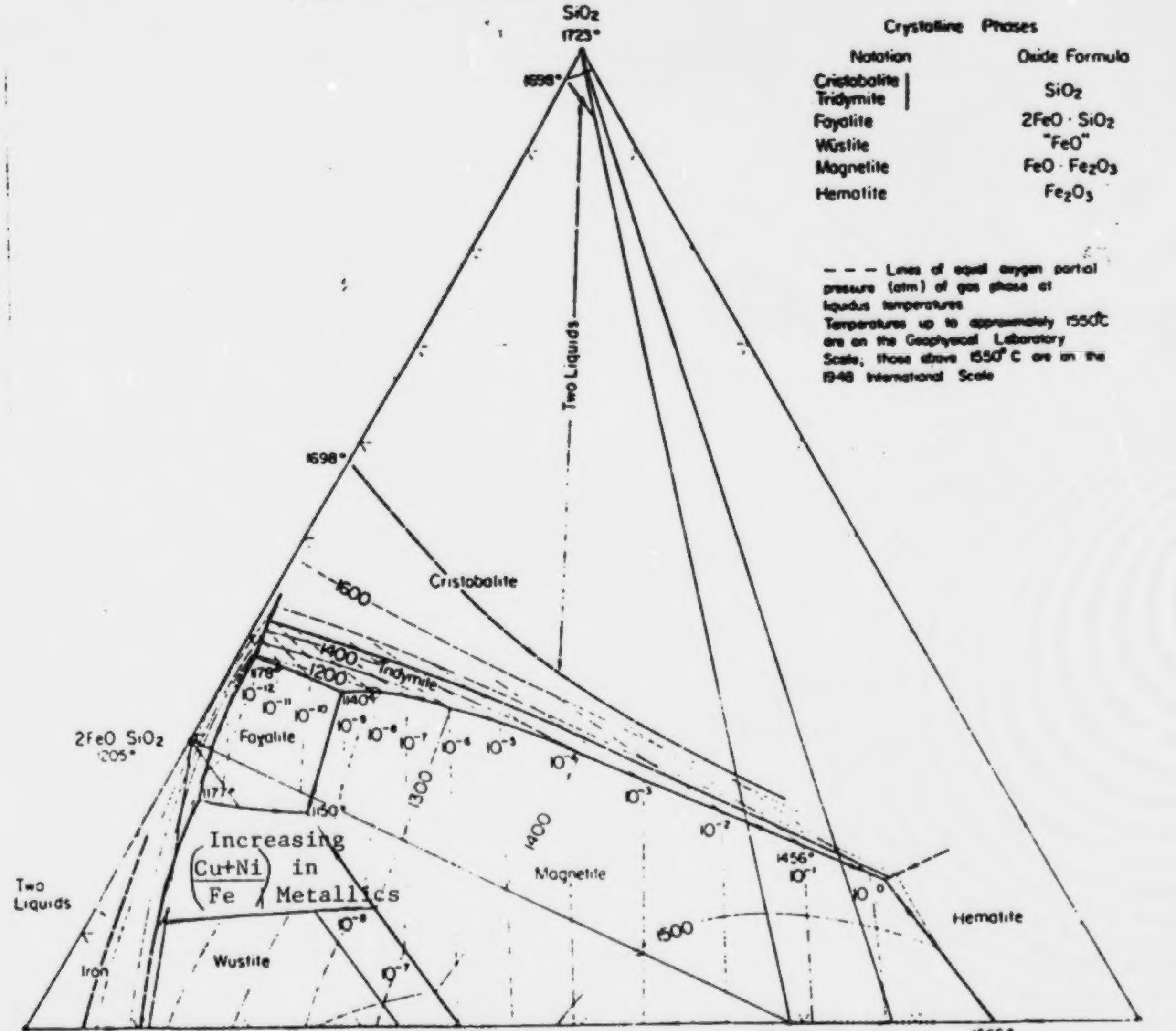
Another reason for the lower matte grade at high coke dosages is that there is less sulphur loss from the system when coke is available as a reductant. The reduction of oxides by FeS with SO_2 evolution is suppressed by carbon reduction. Thus, sulphur elimination during reductive smelting is lower than during "oxidizing" smelting.

The compositions of the metallics in equilibrium with liquid matte provide an index of the oxygen potential of the system at any time during smelting. In Figure 3 the alloy composition shifts towards a lower $\frac{Cu + Ni}{Fe}$ ratio with increasing coke content. Above approximately 1150°C the matte also approaches equilibrium with liquid slag, which may be considered in simplified form to be iron silicate. The region of liquid slag compositions is shown on the FeO-Fe_2O_3-SiO_2 ternary phase diagram in Figure 4 in the fayalite area; equilibrium oxygen pressures are also indicated. Oxygen isobars may also be identified as lines of constant alloy composition, expressed in terms of the $\frac{Cu + Ni}{Fe}$ ratio.

Under conditions of metal and silica saturation the system becomes univariant, such that the alloy composition cannot change independently of Po_2. At 1200°C this value of Po_2 varies from about 3.5×10^{-13} atm at Fe saturation to 10^{-8} atm for Ni saturation.

The progress of reduction by carbon in the temperature range 900-1200°C may be followed with reference to the chemical analyses provided in Table 9, the micrographic results from arrested TGA tests, and the experimental TGA-GC curves. These data are complete for the tests at 67% roast with 5% coke addition.

At 900°C the low temperature reactions are substantially complete and the charge consists of partly altered sulphide, oxide, and silicate constituents which form


SiO2
1723°
1698°
Two Liquids
1698°
Cristobalite
1500
1400
Tridymite
1200
1178°
10^-12
10^-11
10^-10
1140°
Fayalite
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
2FeO SiO2
1205°
1177°
1150°
1300
1400
Magnetite
1456°
1500
Hematite
Increasing
(Cu+Ni)/(Fe) in Metallics
Two Liquids
Iron
Wustite
10^-8
10^-7
FeO
1520°
1369°
1421°
FeO · Fe2O3
1594°
1566°
Fe2O3

Crystalline Phases

Notation	Oxide Formula
Cristobalite Tridymite	SiO_2
Fayalite	$2FeO \cdot SiO_2$
Wüstite	"FeO"
Magnetite	$FeO \cdot Fe_2O_3$
Hematite	Fe_2O_3

– – – Lines of equal oxygen partial pressure (atm) of gas phase at liquidus temperatures

Temperatures up to approximately 1550°C are on the Geophysical Laboratory Scale; those above 1550° C are on the 1948 International Scale

Fig. 4 The FeO-Fe_2O_3-SiO_2 System

**Phase Diagram for Ceramists, E.M. Levin, C.R. Robbins, H.F. McMurdie
The American Ceramic Society, Columbus, Ohio, 1964.**

a porous sinter. Incipient metallization is apparent at 960°C, giving metallic contents of 1.16% Ni, 1.58% Fe, and 0.42% Cu. There is a decrease in Fe^{3+} from 22.5% at 600°C to 17.9% at 960°C, this is an indication of some gaseous CO and direct carbon reduction. However, the strongest reactions occur just above the matte fusion temperature, at 1000-1060°C. The large weight losses as well as CO and CO_2 peak maxima in this range are consistent with the appearance of the charge which provides much evidence of reaction among matte, flux, and graphite. Metallization becomes extensive and most of the magnetite disappears.

From 1060°C to 1250°C there is diminished weight change and gas evolution, coincident with coke depletion. Complete fusion and slag formation occur while metallization progresses further. The composition of metallics also changes with temperature according to the data of Table 10.

TABLE 10: CHEMICAL COMPOSITION OF METALLICS

Temperature	Composition (wt%)				Fe/Ni wt ratio
	Fe	Cu	Co	Ni	
1056°C	62.5	4.57	1.63	32.8	1.91
1100°C	65.2	4.07	1.47	31.4	2.08
1250°C	73.4	4.14	1.21	21.9	3.35

The important trend is the increasing enrichment of the metallics with iron. There is a rise in the Fe/Ni ratio from 1.9 to 3.4 as reduction proceeds towards complete exhaustion of coke.

The influence of the quantity of coke on the high temperature reduction reactions is also displayed by the shapes of the weight loss curves, which are not very different for various degrees of roast, at a constant coke dosage. Curves are displaced by the differing weight losses in the lower temperature region, but could be superimposed to form a single characteristic reduction curve for a given coke addition. Thus, oxide reduction is controlled by coke availability in the range 0-5% coke. The concentration of oxides in calcine is sufficient for complete coke consumption in reduction reactions at the degrees of roast employed in these tests.

The effect of coke dosage on the initiation temperature for rapid reduction is evident in the weight loss curves. A greater quantity of coke presents a larger surface area for reactions with matte and also augments the probability of CO regeneration by reduction of CO_2 at the coke surface. Peak measured CO/CO_2 volume ratios are given as a function of the coke additions in Table 11.

TABLE 9: CHEMICAL ANALYSIS OF PRODUCTS FROM ARRESTED TGA TESTS

EFFECT OF TEMPERATURE (Nitrogen Atmosphere)

% Roast	% Coke	% Lime	T (°C)	Ni	Ni°	Fe	Fe°	Cu	Cu°	S	S^{04}	Fe^{3+}	Fe_3O_4
67.5	5	0	600		0.08		0.03		0.46			22.5	
			900		0.46		1.04		0.40			19.6	
			960		1.16		1.58		0.42			17.9	
			1000	6.3	2.5	38	5.2	6.3	0.56	8.2	<0.03	11.0	22.9
			1056	6.8	4.0	41	19.1	6.5	0.64	8.9		2.24	4.6
			1100	6.7	3.9	41	17.6	6.7	0.68	7.6		1.02	2.1
			1250	10.6	9.2	47	25.2	10.3	0.83	12.0		1.0	2.0

TABLE 11: PEAK CO/CO_2 RATIOS

% Coke	Range of CO/CO_2 Ratios
1	0.3-0.6
3	0.35-1.5
5	1.5-2.6

The increasing CO/CO_2 ratios at higher coke dosages correspond to more reducing conditions in the charge, but also imply a lower efficiency of coke utilization.

6.2.2.4 Reduction Mechanisms

The reduction of a metal oxide, MeO, in the presence of solid carbon may be simply expressed by reactions $MeO + C = Me + CO$ and $MeO + CO = Me + CO_2$. However, the observed rapid reaction rates in the temperature range of 950-1100°C are inconsistent with the known kinetic constraints on the reduction of oxides by CO or directly by carbon. The formation of liquid matte is critical to the establishment of rapid kinetics. Liquid matte bears the capacity to act as an oxygen transfer medium between solid oxides and coke. This matte-assisted reduction mechanism is promoted by several characteristics of liquid matte, as follows:

1. High oxygen solubility (approximately .6 wt% for a 20% Cu, 20% Ni matte).
2. Low fusion temperature. The fusion point of matte is typically <1000°C, and is significantly below the lowest melting point of slag.
3. High fluidity. Liquid mattes provide rapid, good contact between solid oxides and coke particles.

The rapid dissolution of magnetite into FeS and copper matte has been demonstrated previously in experiments reported by Kaiura(1) and Lindon(2). These studies showed that reduction by carbon in contact with matte was much more likely than the $FeS-Fe_3O_4$ reaction, with SO_2 evolution. Such behaviour is congruent with the results of the TGA-GC tests, which showed no SO_2 production in the fusion region at high coke addition levels.

Other possible reduction mechanisms are significantly less favoured than the matte-assisted reaction. Solid state carbon-oxide reactions are severely limited by contact area and would not exhibit the strong temperature dependence which was observed. Gaseous reduction by CO is thermodynamically possible at temperatures above the equilibrium value for the coexistence of MeO, Me, CO, CO_2 and solid carbon. At a total pressure, $P_{CO} + P_{CO2} = 1$ atm, the reduction of all Cu, Ni, Co, and Fe oxides of interest should proceed at temperatures above 650°C. However, the regeneration of product CO_2 at the solid carbon surface by the Boudouard reaction $C + CO_2 = 2CO$ is known to be slow below 1000°C.

The sequence of magnetite reduction by carbon through the liquid matte intermediate may be considered to be sequential, as follows:

$$Fe_3O_4\ (S) = Fe_3O_4\ (\text{dissolved in matte})$$

$$Fe_3O_4\ (\text{in matte}) + C = 3FeO\ (\text{in matte}) + CO\ (g)$$

$$FeO\ (\text{in matte}) + C = Fe\ (\text{in matte}) + CO\ (g)$$

The overall reaction then, is:

$$Fe_3O_4(s) + 4C(s) = 3Fe\ (\text{in matte}) + 4CO\ (g)$$

In terms of reduction by CO this becomes:

$$Fe_3O_4(s) + 4CO\ (g) = 3Fe\ (\text{in matte}) + 4CO_2\ (g)$$

The result of this reaction is the formation of an iron-rich, sulphur deficient matte which can reduce copper, nickel, and cobalt oxides from slag. An increase in the coke addition causes the formation of a larger mass of a lower grade matte which thereby has a greater capability for FeO dissolution.

At higher temperatures slag formation can occur either directly from fusion of flux with oxides, or through the matte by reactions such as the following:

$$2FeO\ (\text{in matte}) + SiO_2 = 2FeO.SiO_2\ (1)$$

$$3FeO.2SiO_2\ (1) + FeO\ (\text{in matte}) = 2(2FeO.SiO_2)\ (1)$$

Thus, when liquid slag has formed, oxygen removal from matte can occur via FeO solution in slag; however, the solubility of FeO in slag is fixed by the matte-slag equilibrium.

From the TGA-GC data it is clear that the rate of oxide reduction in the temperature range 950-1100°C exerts a dominant influence on the smelting rate of partly roasted calcines.

6.2.2.5 High Temperature SO_2 Producing Reactions

In the tests at 0 and 1% coke additions there is a moderate increase in the rate of weight loss above 950°C. In the presence of coke some of this weight change is caused by CO_2 evolution, but for 0% coke the observed loss can only occur by SO_2 escape. The evolution of a small quantity of SO_2 above 900°C, with peaks at approximately 1000°C and 1150°C, is caused by the reaction of liquid matte with oxides in the calcine.

Liquid matte, formed by the fusion of nickel, copper, and iron sulphides at about 950°C, can dissolve a substantial quantity of oxygen as FeO. There is an abundance of magnetite in the calcine which may be reduced by FeS in the matte as follows:

$$3Fe_3O_4\ (\text{solid}) + FeS\ (\text{in matte}) = 10FeO\ (\text{in matte}) + SO_2$$

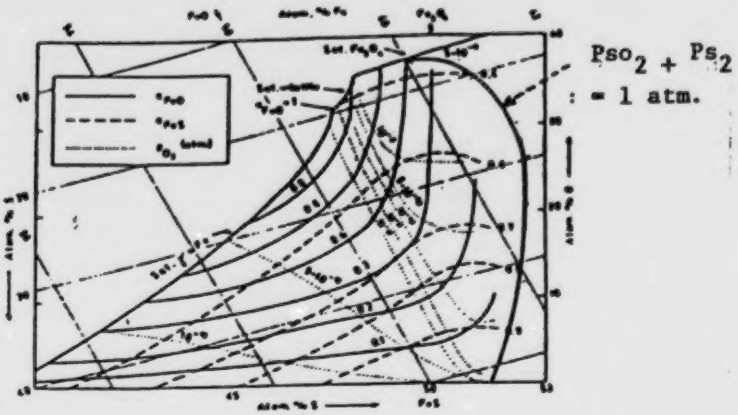


Figure 5: The Fe-S-O Activity Diagram at 1200°C

The discharge of SO_2 can only occur at high Pso_2, say 0.01 atm. and above. There are insufficient thermodynamic data for the Cu-Fe-Ni-S-O system to define the required conditions, but a good indication is available from the Fe-S-O activity diagram of Stofko et al(3), shown in Figure 5.

Upon formation of liquid FeS in matte the dissolution of magnetite occurs rapidly. Near magnetite saturation a sufficiently high Pso_2 for evolution can be achieved. With further dissolution the liquid composition moves towards the Fe_3O_4-'FeO' saturation point where the Pso_2 value is less than 0.01 atm., and the formation of SO_2 gas is depressed.

The second SO_2 peak occurs in the temperature range of flux melting and slag formation. In silica saturated fayalite slags at 1200°C the activity of FeO is fixed at about 0.4. Along the magnetite saturation boundary of the Fe-S-O system the value of $Pso_2 + Ps_2$ increases rapidly as aFeO falls below unity, leading to the second burst of SO_2 at 1150°C.

The degree of roast of calcine affects the strength of high temperature SO_2 production by controlling the availability of FeS, or the matte grade. Oxygen solubility is higher in the low grade mattes formed at low % roast, thereby giving rise to larger Pso_2 values. Coke addition to the charge depresses SO_2 evolution by removing oxygen from the matte. With sufficient coke (3% or more) the reduction of oxides occurs through the liquid matte medium, without SO_2 generation.

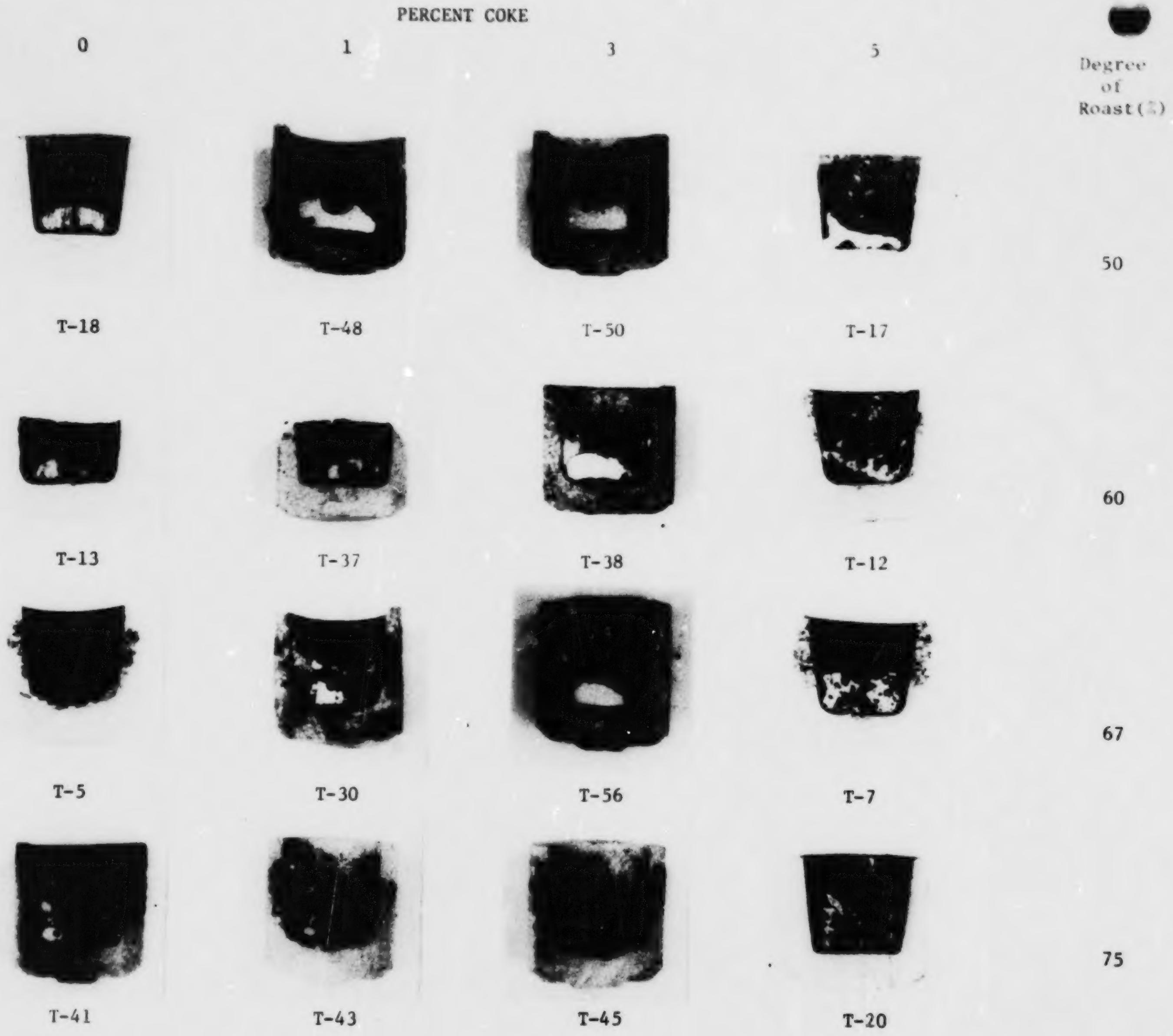

PERCENT COKE
0
1
3
5
Degree of Roast (%)
T-18
T-48
T-50
T-17
50
T-13
T-37
T-38
T-12
60
T-5
T-30
T-56
T-7
67
T-41
T-43
T-45
T-20
75

FIGURE 6: CRUCIBLE CROSS SECTIONS FOR SERIES 1 TESTS.

7.0 NITROGEN ATMOSPHERE: 0-15% LIME ADDITION

Lime was added to the calcine charges to examine the effects on SO_2 evolution and the progress of smelting reactions. Two sets of tests were performed as follows:

1) 67% roast, 5% coke; 0, 5, 10, 15% lime
2) 60% roast, 5% coke; 0, 5, 10, 15% lime

Complete graphical data for these runs as well as lime alone are presented in Appendix 2.

7.1 Lime Alone: Modification of TGA Curves to Correct for Moisture in Lime

The TGA curve for lime heated in a nitrogen atmosphere displays a 24% weight loss in the temperature range 420-600°C, with little CO_2 evolution; this is caused by water loss. Complete dehydration of $Ca(OH)_2$ according to reaction $Ca(OH)_2 = CaO + H_2O$ involves a weight loss of 24%, with P_{H2O} values of 0.15 atm at 427°C and 1.32 atm at 527°C.

At the higher lime addition levels used in these tests (10 and 15%) the weight loss curves are considerably affected by the discharge of water vapour. Since the dehydration reaction has no functional involvement in the smelting process, adjustments have been applied to the curves, and these graphs are also included in Appendix 2. The analysis of data refers to the adjusted values.

7.2 Calcine - Lime Mixtures

7.2.1 Characteristic Features

(1) Weight Changes

The adjusted weight change curves for tests which contain 5, 10, and 15% lime are very close at each degree of roast. There is less weight loss for these mixtures throughout the temperature range than for lime-free charges. With no lime there is a steady, moderate weight loss from 600°C onwards, until rapid reaction occurs at 950-1000°C. By comparison, the charges with added lime have small weight losses up to 800°C (<1%), then a rapid increase at a lower temperature, approximately 900°C.

(2) SO_2 Evolution

Very little SO_2 evolution is observed in the presence of lime, but baseline values for 0% CaO are lacking. Comparisons with the corresponding tests in Series 1 at 3% coke dosage show that lime addition greatly depresses SO_2 evolution.

(3) CO/CO_2 Evolution

In all cases the evolution of CO and CO_2 occurs strongly only above 850°C. The most notable effects of lime addition are:

- large increase in peak heights
- broader peaks, indicating discharge over a wider temperature span
- evolution commences strongly at lower temperatures (850°C instead of 950°C).

7.2.2 Postulated Reactions

Those chemical reactions which occur in lime-free tests carry on, but are joined by reactions which involve lime. The influence of lime addition is considered for lower temperature reactions, from which SO_2 is usually produced, and for higher temperature reduction reactions.

7.2.2.1 SO_2 and SO_3 Absorption Reactions

The general absence of SO_2 in the outlet stream shows that the gases produced by the thermal decomposition of sulphides and sulphates, as well as sulphide-oxide solid state reactions, are absorbed by lime. Two products are possible for these absorption reactions, $CaSO_4$ and CaS. The stabilities of these two are influenced by temperature, supply of carbon, and oxygen potential. Under the test conditions of Series 2 there is no atmospheric oxygen available for the formation of $CaSO_4$, so CaS is more likely to form.

In the temperature range 450-700°C, SO_2 is produced from the thermal decomposition of sulphide minerals. An equilibrium analysis of the reactions which occur when pyrite in the charge is heated with lime and carbon is shown in Table 12.

TABLE 12: EQUILIBRIUM PRODUCTS FOR REACTION $FeS_2 + Fe_2O_3 + CaO + XC =$

Temperature (°C)	X (= Moles Carbon)	Major Stable Products
600	0	0.33 $CaSO_4$, 0.67 CaS, FeS, Fe_3O4
600	0.1	0.28 $CaSO_4$, 0.72 CaS, FeS, Fe_3O_4, CO_2
600	1.0	1.0 CaS, FeS, Fe_3O_4, CO_2, CO, C

In the absence of carbon the formation of $CaSO_4$ is favoured, but limited by the supply of oxygen for the reaction $CaO + SO_2 + 1/2\ O_2 = CaSO_4$. This results in the formation of both $CaSO_4$ and CaS. With carbon added to the charge $CaSO_4$ is reduced to form CaS plus CO and CO_2. The greater concentrations of these gases detected in the range 600-800°C at 5-15% CaO arise from this reduction.

As long as sufficient carbon is present to maintain strongly reducing conditions, any $CaSO_4$ will react to form CaS throughout the charge heating temperature range. There is little temperature effect on the equilibrium compositions shown in Table 12 from 500°C upwards.

At approximately 750-800°C metal sulphates in the calcine become thermally unstable with respect to oxides, producing SO_3 partial pressures greater than 1 atm. Under these more oxidizing conditions lime reacts to form calcium sulphate:

$$CaO + SO_3 = CaSO_4$$

The thermodynamics of this reaction are highly favourable, as the equilibrium P_{SO_3} at 800°C is 10^{-10} atm. With carbon in the charge, reduction of both metal sulphates and $CaSO_4$ can occur, again to produce CaS. The equilibrium products of iron sulphate decomposition in presence of coke and lime are presented in Table 13.

TABLE 13: EQUILIBRIUM PRODUCTS FOR REACTION $yFe_2(SO_4)_3 + C + CaO =$

Temperature (°C)	Y(=Moles Ferric Sulphate)	Major Stable Products
800	1	$CaSO_4$, Fe_2O_3, SO_2, CO_2
800	0.1	CaS, CaO, Fe, FeO, CO_2,CO

The results in Table 13 show that the products of sulphate decomposition and reduction are altered according to the relative amounts of metal sulphate, lime, and carbon. In test series 2, there is a large excess of CaO and the coke in the charge has not been consumed prior to the high temperature reduction phase; thus conditions at y=0.1 are more applicable. There is complete absorption of SO_3 from ferric sulphate, resulting in the formation of CaS and evolution of CO and CO_2. The sharp rise in the CO_2 peaks at 800°C for lime-containing charges is consistent with the position of sulphate decomposition reactions.

7.2.2.2 Reduction Reactions

The major feature of tests with added lime is the large increase in CO and CO_2 volumes in the reduction temperature region. This phenomenon could be caused by the lime-enhanced reduction of sulphides by either of two reactions:

$$MeS + CaO + 1/2C = Me + CaS + 1/2\ CO_2 \quad .... \quad (1)$$

$$MeS + CO + CaO = Me + CaS + CO_2 \quad .... \quad (2)$$

At 927°C both of these reactions are thermodynamically favoured. This is evident from the large values of the equilibrium constants for the sulphides of interest in Table 14.

TABLE 14: EQUILIBRIUM CONSTANTS FOR LIME-ENHANCED REDUCTION OF SULPHIDE

Sulphide	Equilibrium Constant at 927°C K(1)	K(2)
Ni_3S_2	57.7	2.9
FeS	12.9	1.8
Cu_2S	3.5	0.5

A calculation of the equilibrium among FeS, CaO, and C at 900-1100°C identifies the stable products, given in Table 15.

TABLE 15: EQUILIBRIUM PRODUCTS FOR REACTION FeS + CaO + ZC =

Temperature (°C)	Z (= Moles Carbon)	Major Stable Products
900-1100	1	CO, CaS, Fe
1000	0.5	CO, CO_2, CaS, Fe, FeO
1000	0.01	CO, CO_2, CaS, Fe, FeO

The table shows that sulphide reduction is feasible, with the capture of all sulphur as CaS. The degree of metallization of FeS is dependent upon the quantity of carbon available.

It has been reported(4) that lime typically enhances the kinetics of sulphide reduction significantly. There is some indication which confirms this action in the TGA tests. The earlier initiation of rapid weight loss in lime-bearing charges must be caused by CO and CO_2 discharge at lower temperatures.

8.0 AIR ATMOSPHERE

Graphical results are given in Appendix 3 for tests conducted in air on lime-free calcine charges and on coke alone. An example has been brought forward in this section to illustrate trends, as Figure 7, "Trend Graphs for Series 3 Tests - Air, Atmosphere, No Lime". This has been annotated to show qualitatively the most important effects of the variables.

8.1 Coke Alone

The weight loss curve shows that coke combustion commences at 450°C and proceeds at a nearly linear rate to completion at 1000°C. There is CO_2 evolution throughout this temperature range at a substantially constant rate. The appearance of a CO peak at 500°C is surprising, as oxidation should occur between the coke surface and the inlet of the gas sampling tube.

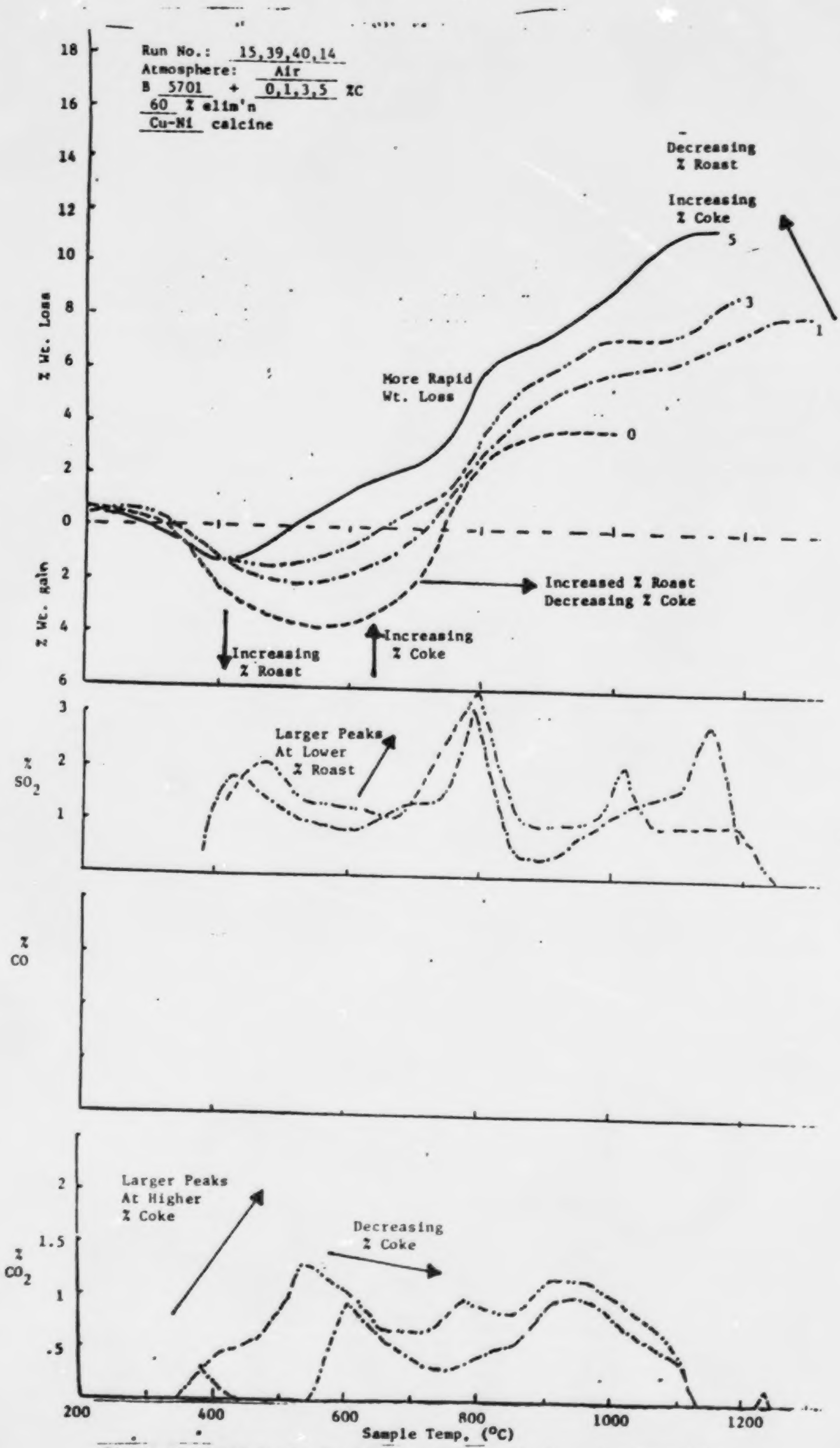


Figure 7: Trend Graphs for Series 3 Tests: Air Atmosphere, No Lime

8.2 Calcine Tests in Air

8.2.1 Characteristic Features

The TGA-GC data for tests performed in an air atmosphere are considerably more complex than for nitrogen. An analysis of all features is not feasible; only the major events and trends will be considered.

(1) Weight Changes:

A small weight loss is recorded up to 300°C, followed by a rapid weight gain. The amount of gain is much larger for samples at high degrees of roast and low coke additions. Also, the transition temperature from weight gain to further loss is much lower at large coke addition levels. A corresponding, but weaker trend exists towards increased transition temperatures at higher degrees of roast. The initial period of weight loss extends to approximately 700-750°C, and is followed by a small region of more rapid loss. At 800-850°C the rate of loss again decreases. There appears to be a strong influence of coke addition levels, particularly associated with the increase from 3% to 5%. At 5% coke there is a much closer coincidence of the curves for different degrees of roast, indicating the dominant influence of coke supply. In addition, the coke dosage has a greater effect on more highly roasted samples.

(2) SO_2 Evolution:

SO_2 is detected throughout the temperature range 400-1200°C, with peaks at approximately 500, 800, and 1150°C. Peak heights are generally larger for less roasted calcines.

(3) CO/CO_2 Evolution:

CO was oxidized in air above the charge and was usually not detected. CO_2 was evolved between 300 and 1200°C, with major amounts at 600°C and 900-1000°C. At higher coke dosages the CO_2 peaks commence at lower temperatures, and are larger.

8.2.2 Postulated Reactions

The same reactions which occur under nitrogen cover also proceed in air. Additional important air-charge reactions impress considerable changes on the behaviour of the system, and will be considered in greater detail.

8.2.2.1 Low Temperature Reactions (<300°C)

The small weight losses in the low temperature range are probably due to drying of free moisture or dehydration of bound water from the calcine. This region is curtailed by the rapid onset of weight gains through sulphate formation.

8.2.2.2 Sulphate Formation (300-680°C)

Weight gains must be caused by oxygen uptake from reactions between solid sulphides and air, with the formation of metal sulphates. The overall reaction is $MeS + 2O_2 = MeSO_4$, but the actual path is more complex, proceeding through oxide and perhaps basic sulphate intermediates. Sulphate formation is favoured by a high partial pressure of SO_3 for the general reaction

$$MeO + SO_3 = MeSO_4$$

In the presence of air, the SO_3 arises from the oxidation of SO_2 evolved during roasting (sulphide-air) reactions.

The metal sulphates of interest here are generally stable below 700°C in the absence of carbon. Relative thermal stabilities with respect to oxides can be allocated by the decomposition pressures listed in Table 6, to form the following order:

$Fe_2(SO_4)$ - least stable
$CuSO_4$
$CuO.CuSO_4$
$NiSO_4$
$CoSO_4$ - most stable

The weight change curves indicate that the formation of sulphates is strongly suppressed by the addition of coke. The diminished stabilities of sulphates in contact with solid coke were previously shown by Table 7, "Equilibrium Products for Carbon-Sulphate Reactions". To examine this phenomenon TGA tests with 0 to 5% coke were arrested at 600°C. Results of chemical analyses are presented in Table 16. These results partly support the TGA data by showing a large decrease in the concentration of sulphates, and particularly copper sulphate, as 1% coke is added to the charge. This result is consistent with the very large difference in weight gains for 0% and 1% coke charges. However, the additional differences in weight gain which are noted as coke addition is raised to 5% are not confirmed by the chemical data, which show no further change in the extent of sulphate formation. The major part of the reduced weight gains at coke additions above 1% must be attributed to coke combustion.

TABLE 16: EFFECT OF % COKE ON SULPHATE FORMATION (Air Atmosphere)

% Roast	% Coke	% Lime	T(°C)	w.s. Ni	w.s. Fe	w.s. Cu	w.s. Co	S	S^{SO4}	w.s. Cu/Ni	w.s. Fe/Ni
67	0	0	600	1.13	0.25	3.06	0.09	6.0	3.1	2.7	0.22
67	1	0	600	0.40	0.40	1.27	0.04	7.4	1.6	3.2	1
67	3	0	600	0.41	0.27	1.41	0.04	7.0	1.6	3.4	0.66
67	5	0	600	0.42	0.06	1.33	0.04	6.3	1.4	3.2	0.14

(w.s. = water soluble)

As the coke content is raised, the ratio of copper:nickel sulphates changes only slightly, but the relative quantity of iron sulphates, expressed by the water soluble Fe:Ni ratio, decreases considerably (the value at 0% coke is inexplicably low). This trend is consistent with the lower stability of $Fe_2(SO_4)_2$ compared with $CuSO_4$ and $NiSO_4$ as the PO_2 value is decreased in the presence of more coke.

From the TGA tests it is evident that the apparent weight gain is greater for more highly roasted samples. Additional tests were carried out at different degrees of roast and arrested at 600°C; chemical analyses are presented in Table 17. According to these results the quantity of sulphates formed depends only slightly on the degree of roast. If a correction is made for the different concentration of sulphates in the original calcines, then the amounts of new sulphate formed are nearly identical for all degrees of roast. The sulphur balance indicates that the amount of sulphur lost during the heating to 600°C is larger at lower degrees of roast. This trend is in accord with expectations for loss of SO_2 by reactions between air and sulphides in the calcine. The relative sizes of SO_2 peaks confirm this. Thus, the behaviour of the system up to about 650°C is controlled by a balance between sulphate formation, SO_2 gas evolution, and coke combustion. At low % roast the sulphide-air reaction is relatively more important than sulphate formation.

TABLE 17: EFFECT OF % ROAST OF CALCINE ON SULPHATE FORMATION (Air Atmosphere)

% Roast	% Coke	% Lime	T(°C)	w.s. Ni	w.s. Fe	w.s. Cu	w.s. Co	S	S^{SO4}	w.s. Cu/Ni	w.s. Fe/Ni
50	0	0	600	0.36	1.38	1.14	0.05	12.5	2.3	3.2	3.8
60	0	0	600	0.45	0.80	1.39	0.04	9.7	1.9	3.1	1.8
75	0	0	600	0.45	0.51	1.73	0.05	5.5	1.9	3.8	1.1

(w.s. = water soluble)

As the degree of sulphur elimination is increased, the composition of the sulphate changes. The ratio of water soluble Cu:Ni remains reasonably constant but the amount of iron sulphate decreases. The greater abundance of iron sulphides at lower % roast indicates that iron sulphate forms more readily from iron sulphide than iron oxide.

8.2.2.3 Solid Sulphide - Air Reactions (350-900°C)

Roasting reactions between air and solid sulphides account for much of the SO_2 release in these tests. The low starting temperatures for substantial SO_2 evolution, less than 400°C, is consistent with the usual values of ignition points of sulphide minerals in air. The first SO_2 peak at approximately 500°C develops from sulphide ignition, then is followed by a sustained high level of discharge.

Reactions are of the type $Cu_2S + 1/2\ O_2 = Cu_2O + SO_2$ where the resultant SO_2 is either released to the gas stream or oxidized to participate in the sulphate formation-decomposition cycle. As expected, the SO_2 strength is much higher than under a nitrogen atmosphere, where the only oxygen resides in the calcine itself. Also included here, is the thermal decomposition of residual unaltered sulphide minerals such as chalcopyrite according to the following reaction:

$$CuFeS_2 = iss + FeS_2$$

Further reaction of the products with oxygen leads to the following overall reaction.

$$4CuFeS_2 + 9O_2 = 2Cu_2S + 2Fe_2O_3 + 6SO_2$$

The greater availability of sulphides at lower degrees of roast is the dominating influence on weight loss and SO_2 evolution. At lower % roast, the sulphide-air reactions commence at slightly lower temperatures and give rise to much higher weight losses and SO_2 discharge. There is also an earlier (lower temperature) change from net weight gain to weight loss in less roasted calcines. This is an indication that the availability of sulphides influences the sulphide-air reaction more than the sulphate formation reactions.

The roasting reactions continue throughout the temperature range of these tests, as long as unreacted sulphides exist. Above 800°C, at higher degrees of roast, the rate of weight loss diminishes sharply as the sulphur in the calcine is depleted. Eventually, all of the charges become totally oxidized in the steady stream of air. Thus, there is no matte formation and the final appearance of the crucible contents is powdery.

In the absence of coke, the balance between SO_2 evolution and sulphate formation determines the weight changes in the system up to 700°C. With coke added the combustion reaction forces a more rapid turnaround from weight gain to loss. It is expected that the competition for oxygen between coke and sulphide should inhibit the roasting reaction at high coke dosages, but the coincident weight loss from coke combustion is impressed upon the curves.

8.2.2.4 Coke-Air Reaction (400-1200°C)

Coke is oxidized at temperatures down to 400°C, but the reaction becomes vigorous at approximately 450°C and proceeds at a high level to 1200°C. For the first (lower temperature) peak the amount of CO_2 evolved is larger and the temperature at which rapid oxidation begins is lower at higher coke addition levels, due to the increased surface area of coke.

There is no apparent effect of the degree of roast. Following the initial CO_2 peak, there is some decrease until the second peak, associated with oxide reduction reactions, appears at 900-1000°C. This reduced CO_2 evolution in the intermediate temperature range, is caused by depletion of coke near the surface of the charge, with the subsequent requirement for gas penetration into the calcine.

The direct combustion of coke which occurs in these tests, imposes a component of weight loss which is independent of the calcine because the mass of carbon lost depends solely upon the amount of coke added to the charge. In evaluating the TGA curves at different coke additions, it must be noted that the difference in weight losses from the calcine is considerably magnified by this effect.

8.2.2.5 Solid State Sulphide-Oxide Reactions

Solid state sulphide-oxide reactions similar to those which are important in tests performed under nitrogen should also be active during the tests in air. It is not possible to discriminate between solid state and gas solid reactions, but it is reasonable to expect that the sulphide-air reaction would be much more rapid.

8.2.2.6 Sulphate Decomposition (700-830°C)

The accelerated weight loss between 750 and 800°C as well as sharp SO_2 peaks centred at approximately 800°C originate from the thermal decomposition of metal sulphates by reactions of the type:

$$1/3\ Fe_2(SO_4)_3 = 1/3\ Fe_2O_3 + SO_3$$

$$SO_3 = SO_2 + 1/2\ O_2$$

As the reactions are similar in air and nitrogen, the discussion presented in Section 6 is applicable.

The effect of temperature on sulphate decomposition was investigated by arrested TGA tests on calcines roasted to 60% sulphur elimination. The chemical analyses given in Table 18 show that the major part of sulphate breakdown occurs between 700 and 800°C. Between 600 and 700°C, the total quantity of sulphates remains constant but the composition becomes iron-poor.

Iron sulphate is less thermally stable than copper and nickel sulphates. At approximately 700°C, the partial pressure of SO_3 above $Fe_2(SO_4)_3$ is sufficiently high for rapid breakdown to Fe_2O_3. Other sulphates, such as $CuO.CuSO_4$ and $NiSO_4$ can continue to form under these condition and then decompose substantially by 800°C.

TABLE 18: EFFECT OF TEMPERATURE ON SULPHATE DECOMPOSITION (Air Atmosphere)

% Roast	% Coke	% Lime	T (°C)	w.s. Ni	w.s. Fe	w.s. Cu	w.s. Co	S	SSO_4	w.s. Cu/Ni	w.s. Fe/Ni
60	0	0	600	0.45	0.80	1.39			1.94	3.1	1.8
60	3	0	700	0.85	0.04	2.05	0.07	7.0	1.98	2.4	0.05
60	3	0	800	0.30	0.01	0.99	0.03	6.1	0.72	3.3	0.03

The concentration of SO_2 detected in the gas stream is greater for charges with a lower coke addition. This trend is consistent with the depressing effect of coke on sulphate formation previously noted in Table 7.

8.2.2.7 Reduction Reaction (850-1200°C)

For the tests conducted in an air atmosphere, the region of very rapid reduction seen in the nitrogen tests is absent. Under the conditions of constant oxygen supply the coke does not act as an effective reductant because it is depleted by combustion before the temperature rises sufficiently for rapid coke-charge reactions.

The TGA curves show that the rate and total amount of weight loss are higher at larger coke additions. Corresponding CO_2 concentrations also follow the same trend. An estimate of the fraction of coke which is directly combusted with atmospheric oxygen in Series 3 is available by examination of the terminal weight losses at 1200°C. By assuming that all of the carbon is burnt in air, the adjusted terminal weight losses are calculated for Table 19.

TABLE 19: TERMINAL WEIGHT LOSSES FOR SERIES 3 ADJUSTED FOR COKE COMBUSTION

	Adjusted Weight Loss (%) at 1200°C			
% Roast	0% Coke	1% Coke	3% Coke	5% Coke
50	7.5	8.5	8.5	8
60	* 4	6.2	6.0	6.5
67	4	5.5	5.5	4.5
75	2.5	3.5	3.5	4

* test terminated at 1000°C

The proximity of values at each degree of roast is a good indication that much of the coke is simply discharged from the system without reacting with the charge.

A second comparison can be made between the final weight losses in Series 3 (air) and Series 1 (nitrogen). Taking unadjusted data in both cases, the values given in Table 20 are obtained.

TABLE 20: COMPARISON OF TERMINAL WEIGHT LOSSES - N_2 AND AIR ATMOSPHERES

	% Coke							
	5		3		1		0	
% Roast	N_2	Air	N_2	Air	N_2	Air	N_2	Air
50	16	13	10	13	9	10	8	7.5
60	16	11	10	9	8	8		
67	15	9	11	9	7	6	6	4
75	15	8	11	6	6	4	6	3

In most cases, there is a larger final weight loss for calcine charges heated under nitrogen. The differences become particularly large at high coke dosages and high degrees of roast. Under both air and nitrogen conditions, all of the coke is consumed by conversion to CO_2 and CO. In air, the principal reaction occurs with the atmosphere, removing no oxygen from the charge. Under nitrogen cover, only reduction reactions can occur, with the corresponding weight loss from the calcine. There is an effect of % roast on weight differences in Table 20, caused by the increasing activity of the sulphide-air reaction in the presence of larger quantities of sulphides, i.e. at lower degrees of roast. Thus, the difference in weight change due to oxygen removal from the calcine is increasingly countered by sulphur removal in oxidation or roasting reactions as the % roast is decreased.

8.2.2.8 High Temperature Air-Sulphide Reactions (1000-1200°C)

The increased evolution of SO_2 above 1000°C is indicative of a change to the continuing air-sulphide reactions. There is a corresponding small increase in the rates of weight loss in several cases. Fusion of matte constituents occurs just as the coke is becoming depleted. Liquid sulphides are then in better contact with oxygen, which is decreasingly removed by reaction with carbon.

9.0 CONCLUSIONS

9.1 Summary of Results

The data from this testwork, in conjunction with thermodynamic analysis, have been applied to select the probable sequence of chemical reactions in the heating and fusion stages of electric smelting. These are classified according to the temperature range of occurrence in Figure 8 (nitrogen atmosphere) and Figure 9 (air atmosphere).

Many similar reactions occur under both oxidizing and neutral atmospheres; i.e. drying/dehydration, thermal decomposition of sulphides, sulphide-oxide reactions and sulphate decomposition. With a supply of gaseous oxygen, the interaction of air and charge becomes the dominant feature of the system, through secondary roasting, sulphate formation and coke combustion. High temperature smelting reactions occur in absence of air. These consist primarily of oxide reduction by coke and secondarily, reduction by iron sulphide. Further reactions are indicated if lime is incorporated within the charge, principally SO_2 absorption.

There is substantial overlap of the temperature span of some reactions, with possible confounding of TGA-GC data. In particular, the placement of the weaker, extended reactions, such as solid state sulphide-oxide interactions, is less precise due to the masking effect of more active events.

Figures 8 and 9 also constitute a graphic display of reactions within a vertical section of the charge layer in an electric smelting furnace, showing the series of reaction zones encountered by a unit of charge during its progress from the freeboard to the liquid slag. Heating by slag resistance establishes a temperature gradient, from approximately 500°C at the freeboard to 1230°C at the slag. Thus, low temperature reactions occur partly in contact with ingress air to the furnace. A full range of reactions should appear early in charge heating, but air-charge reactions diminish at greater depth within the bed. The oxygen supply is limited both by the need for diffusion into the charge layer and the increasing reactivity of coke at higher temperatures.

The results from this testwork are highly relevant to electric smelting practice for highly roasted calcines. In the following sections some important aspects will be considered in this context.

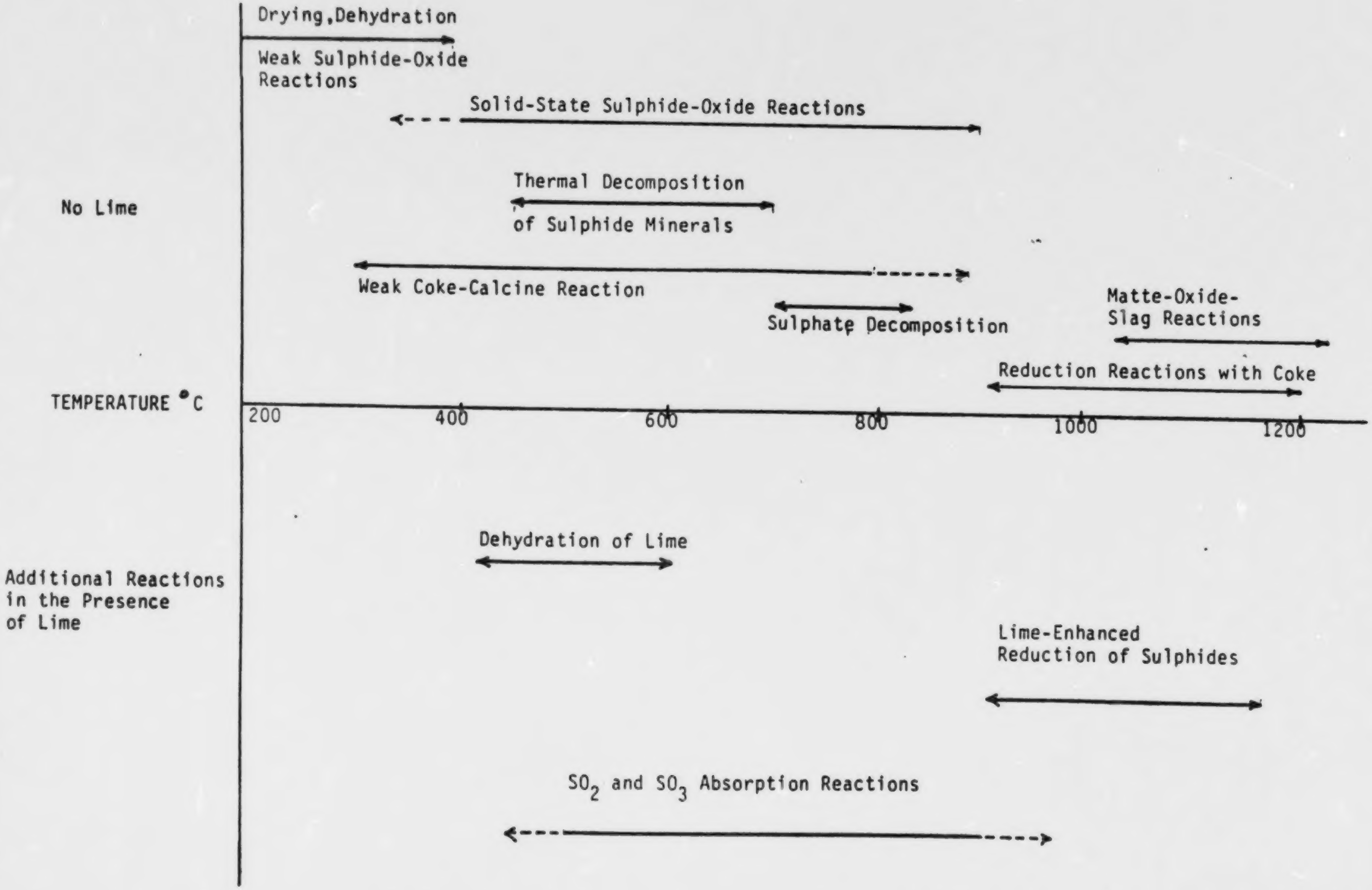


Fig. 8 Temperature Ranges for Reactions : Nitrogen Atmosphere

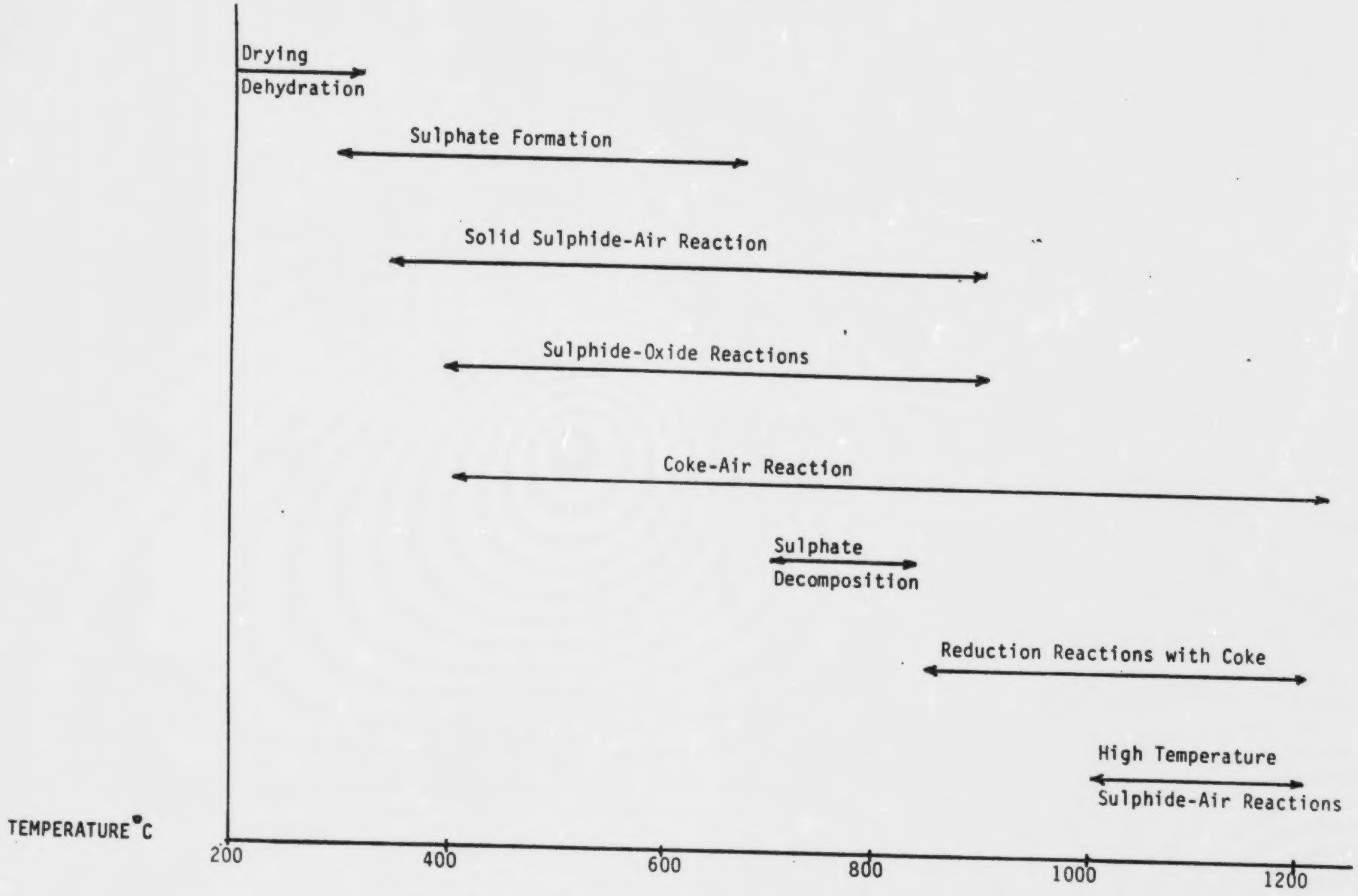


Fig. 9 Temperature Ranges for Reactions : Air Atmosphere

9.2 Degree of Sulphur Elimination

Environmental considerations favour the maximization of sulphur elimination from concentrate prior to electric smelting. Two characteristics of highly roasted calcines have the greatest importance in smelting, lower availability of sulphur and higher input of oxygen.

The sulphur content of calcine affects the release of SO_2 during the charge heating period of smelting. Low strength SO_2 in the offgas is difficult to recover and thus is undesirable. The general trend shown in the experimental work was the inverse relationship between the volume of SO_2 and the degree of sulphur elimination from calcine by prior roasting. Each of the SO_2-producing reactions is influenced by a lower sulphur content in the calcine.

Increased desulphurization is achieved by roasting concentrates at higher temperatures. Under these conditions, the kinetics of mineral decomposition are faster and a larger part of the labile sulphur is removed. Higher temperature roasting also depresses the formation of metal sulphates in the calcine. These **original** sulphates contribute directly to SO_3 and SO_2 formation in the electric furnace by undergoing thermal decomposition. Any decrease in sulphate formation in the roasters is beneficial both in terms of lower SO_2 formation and lower oxygen input to smelting.

Air-sulphide or secondary roasting reactions occur to an extent which is determined by sulphide and oxygen supply. The lesser abundance of mineral sulphides in highly roasted calcines presents a lower surface area for these reactions and decreases SO_2 formation. Since these reactions depend upon the diffusion of oxygen into the charge, SO_2 formation would be depressed by features which inhibit this supply, such as operation with a deeper calcine layer.

In the fusion temperature region, the smelting chemistry is sensitive to both the extra oxygen input and reduced sulphur content of highly roasted calcines. The mass of matte formed is diminished by the limited availability of sulphur and the preferential distribution of oxidized iron to the slag. Thus, a smaller quantity of higher grade matte forms when highly roasted calcines are introduced. Concurrently, valuable metals (Co, Ni, Cu) are also partly oxidized to slag, presenting the requirement for the addition of a reductant.

9.3 Utilization of Coke

Consistent with the overall objective of smelting more highly roasted calcines, it is necessary to provide more reduction capacity to recover valuable metal oxides from slag. The coke added to the charge may react in various ways, some of which are unproductive. Substantial coke burnoff can occur through contact with ingress oxygen at temperatures above 300°C. Direct coke combustion is disadvantageous in two ways. First, there is wastage of coke and diminished availability for metal oxide reduction. Second, the combustion of carbon monoxide in the furnace freeboard may cause unacceptably high temperatures. The latter reason constitutes a practical limitation on coke feedrate.

Below the fusion temperature, other reactions involving coke are less important than direct combustion. Solid state reduction is slow, but some reduction of sulphates can occur. This reaction also consumes carbon, but is not functionally required because of the inevitable thermal decomposition of these sulphates at higher temperatures.

The conceptual requirement to obtain higher coke utilization is for a reductant with sufficiently low reactivity at lower temperatures, to inhibit combustion. Different coke types or granulometry may be effective for this purpose.

Productive coke involvement in electric smelting is primarily in the matte-assisted reduction of oxides. These reactions are very rapid and may be tolerant of different coke feeds. High temperature smelting reactions are limited by coke supply, up to the 5% addition level. Reductant consumption within this regime is complete and rapid.

If a greater degree of reduction is achieved, the metal saturation constraint could be reached. The reduction of excessive quantities of iron into matte can cause furnace operating problems by precipitation of an alloy which accretes in the hearth.

9.4 Lime Addition

The outstanding consequence of lime addition to the charge is the suppression of SO_2 release during smelting. At high degrees of roast of calcine, such as 67%, the SO_2 capture is nearly complete at lime dosages from 5% to 15%. The stable sulphur-bearing compound under reducing conditions is CaS, though $CaSO_4$ may also exist.

The primary benefit of lime addition is the absorption of SO_2 evolved from the reactions in the charge heating temperature range, up to 950°C. At higher temperatures, the reduction reactions may be enhanced by lime. Earlier, more rapid reaction was noted in the testwork, but there was little effect on the final results.

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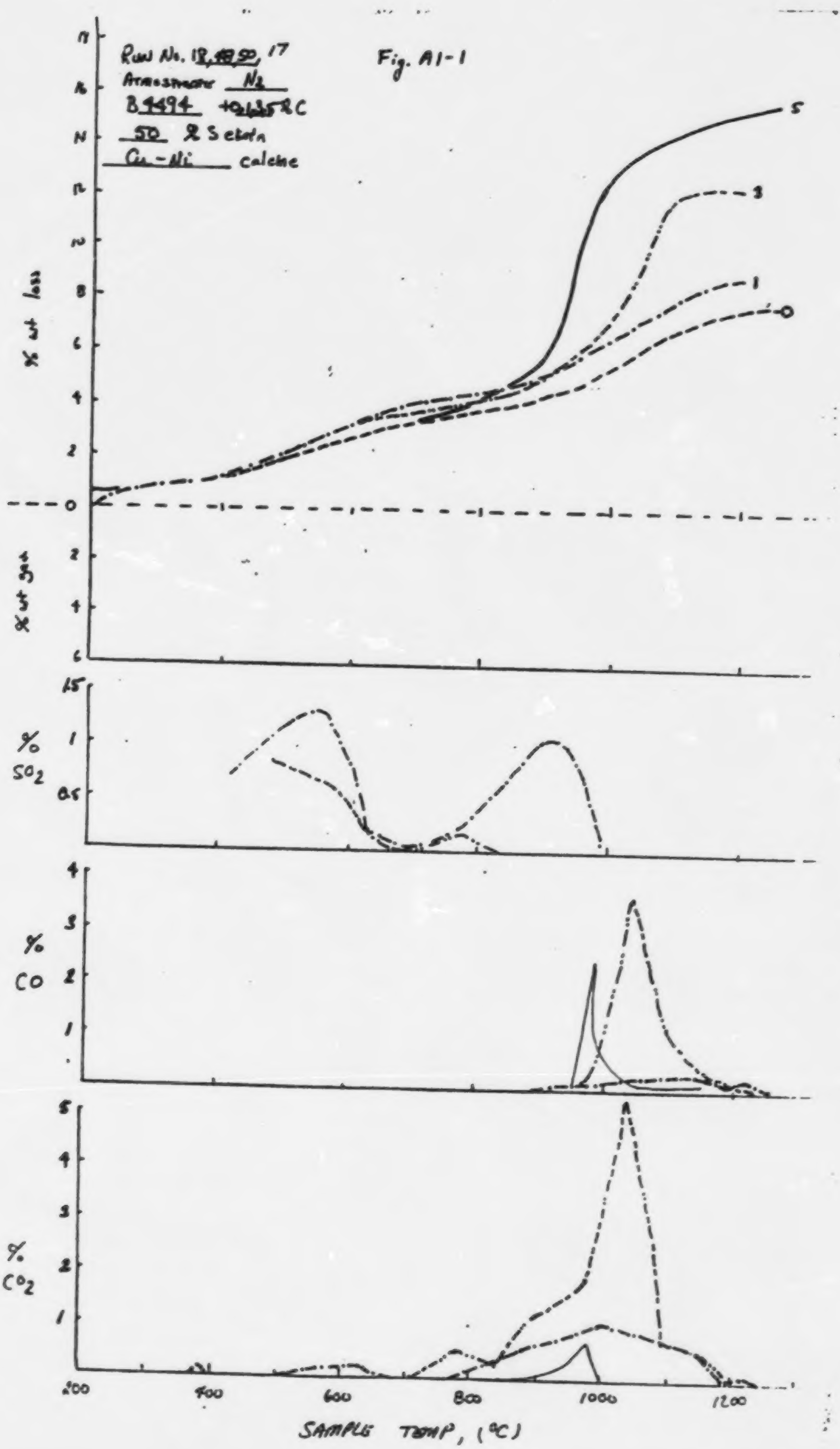
1909K Street, N.W.
Washington D.C. 20006, U.S.A.

APPENDIX 1

GRAPHICAL RESULTS FOR TEST SERIES 1: NITROGEN ATMOSPHERE, NO LIME

Fig. No.	% Roast of Calcine	% Coke Addition
A1-1	50	0-5
A1-2	60	0-5
A1-3	67	0-5
A1-4	75	0-5
A1-5	50-75	0
A1-6	50-75	1
A1-7	50-75	3
A1-8	50-75	5

Fig. A1-1



Run No. 18,49,50, 17
Atmosphere N2
B4494 +0.135 % C
50 % S elem
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
5
3
1
0
% SO2
1.5
1
0.5
% CO
4
3
2
1
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

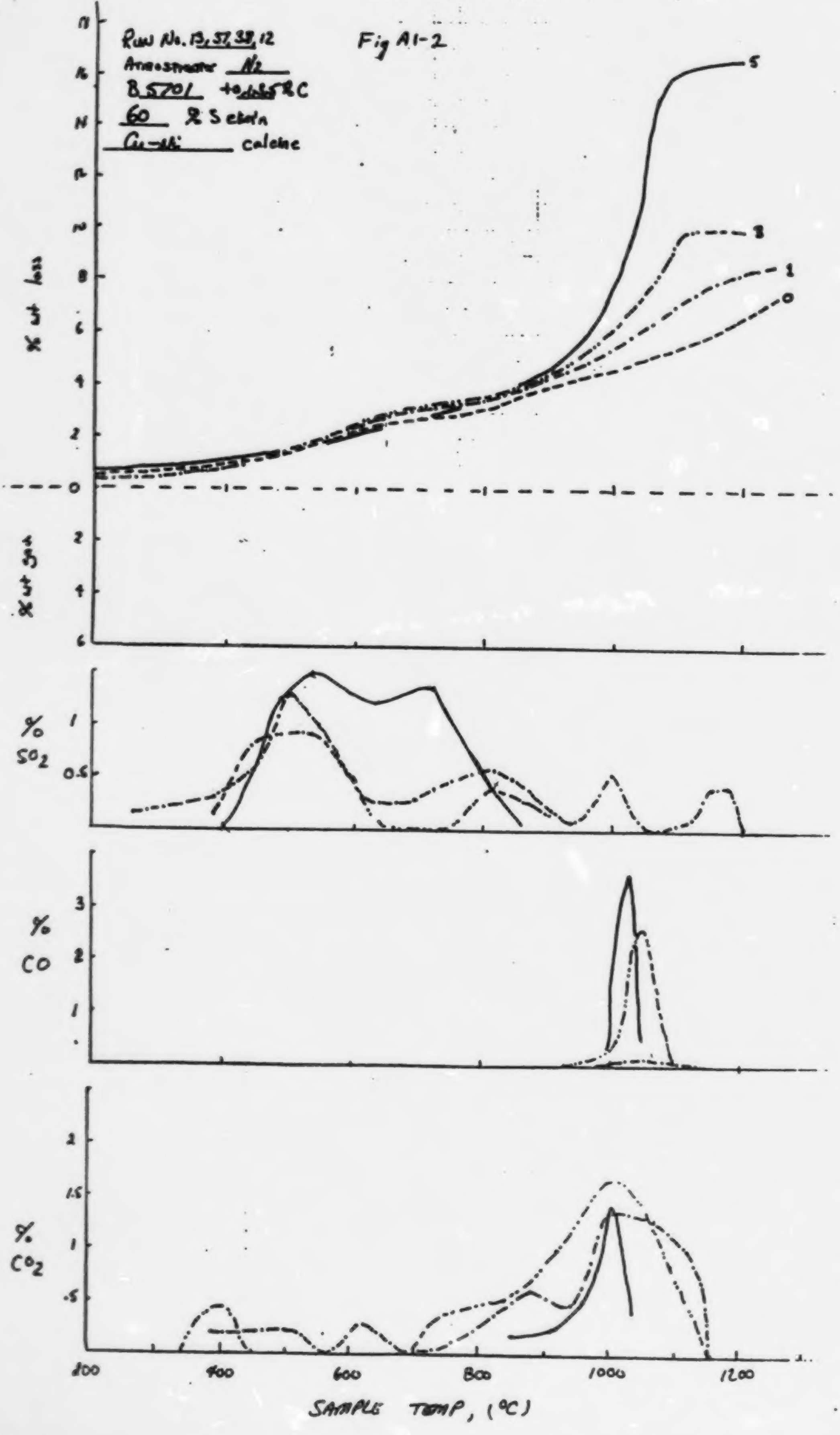


Fig A1-2

Run No. 13, 37, 38, 12
Atmosphere N2
B 5701 +0.065 % C
60 % S elmin
Cu-Ni calcine
% wt loss
18
16
14
12
10
8
6
4
2
0
% wt gain
2
4
6
5
3
1
0
% SO2
1
0.5
% CO
3
2
1
% CO2
2
1.5
1
.5
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig A1-3

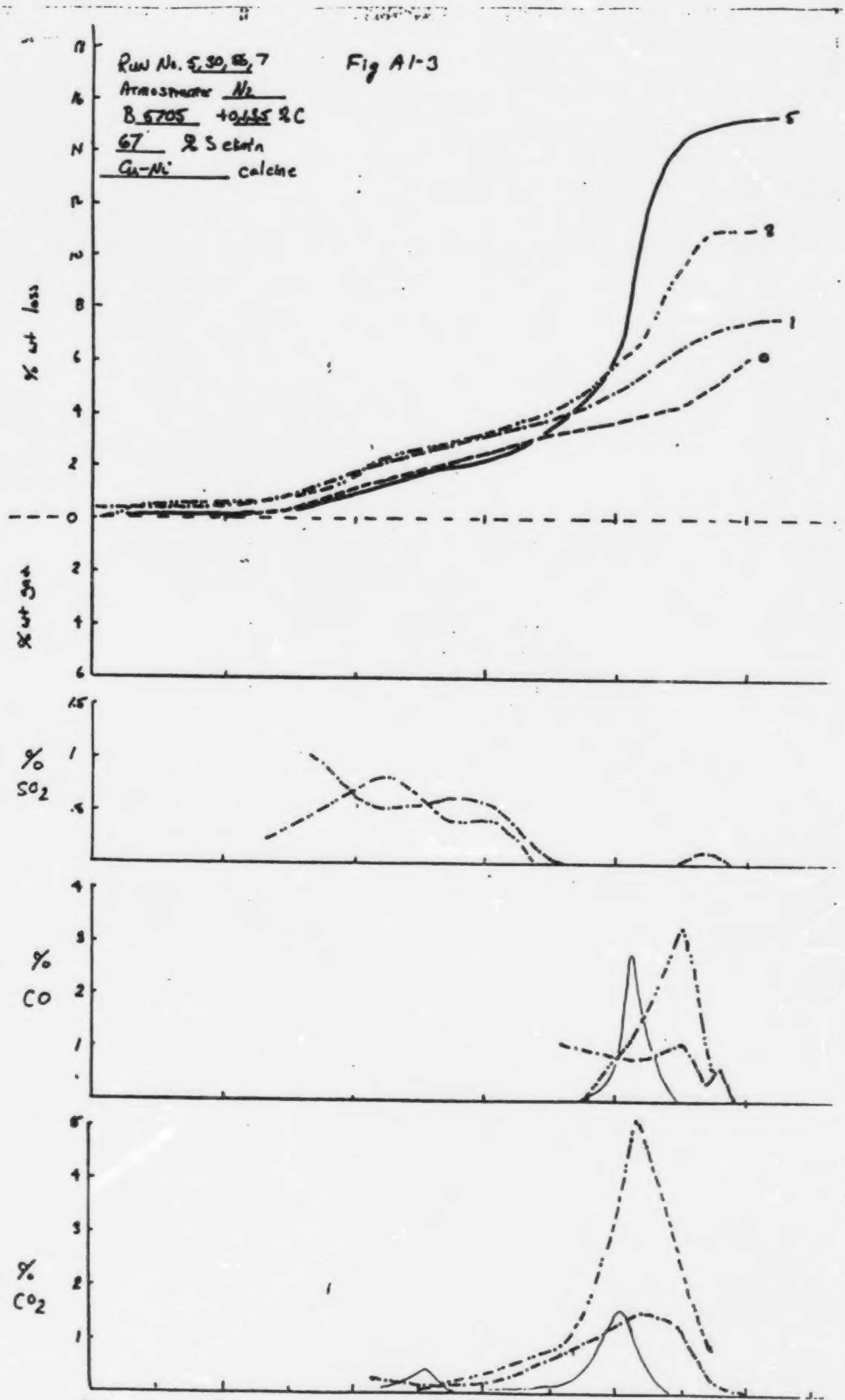
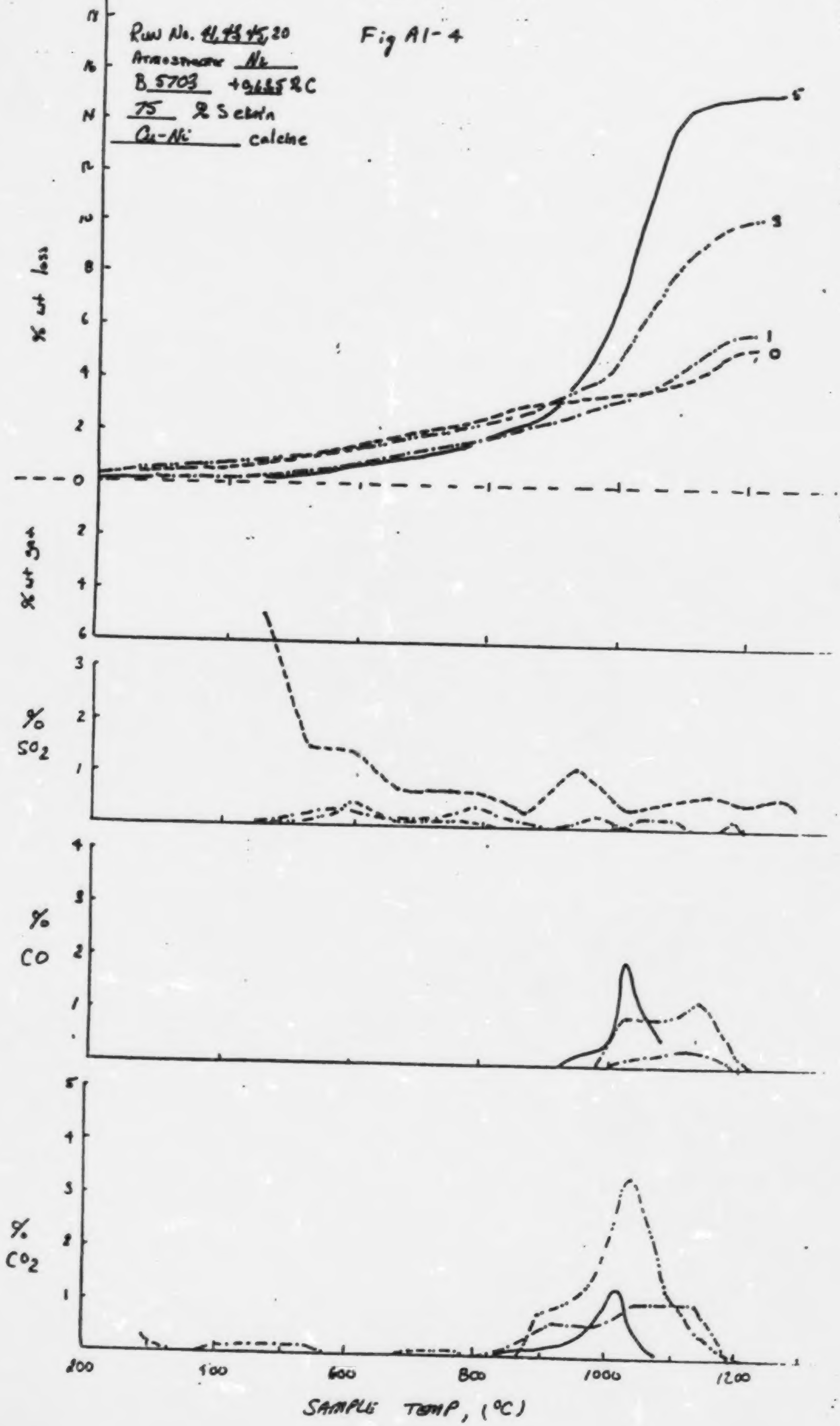

Run No. 5, 30, 35, 7
Atmosphere N2
B 5705 +0.155 % C
67 % S elmin
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
5
8
1
6
% SO2
1.5
1
.5
% CO
4
3
2
1
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig A1-4


Run No. 41,43,45,20
Atmosphere N2
B 5703 +0.685 % C
75 % S chain
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
5
3
1
0
% SO2
3
2
1
% CO
4
3
2
1
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

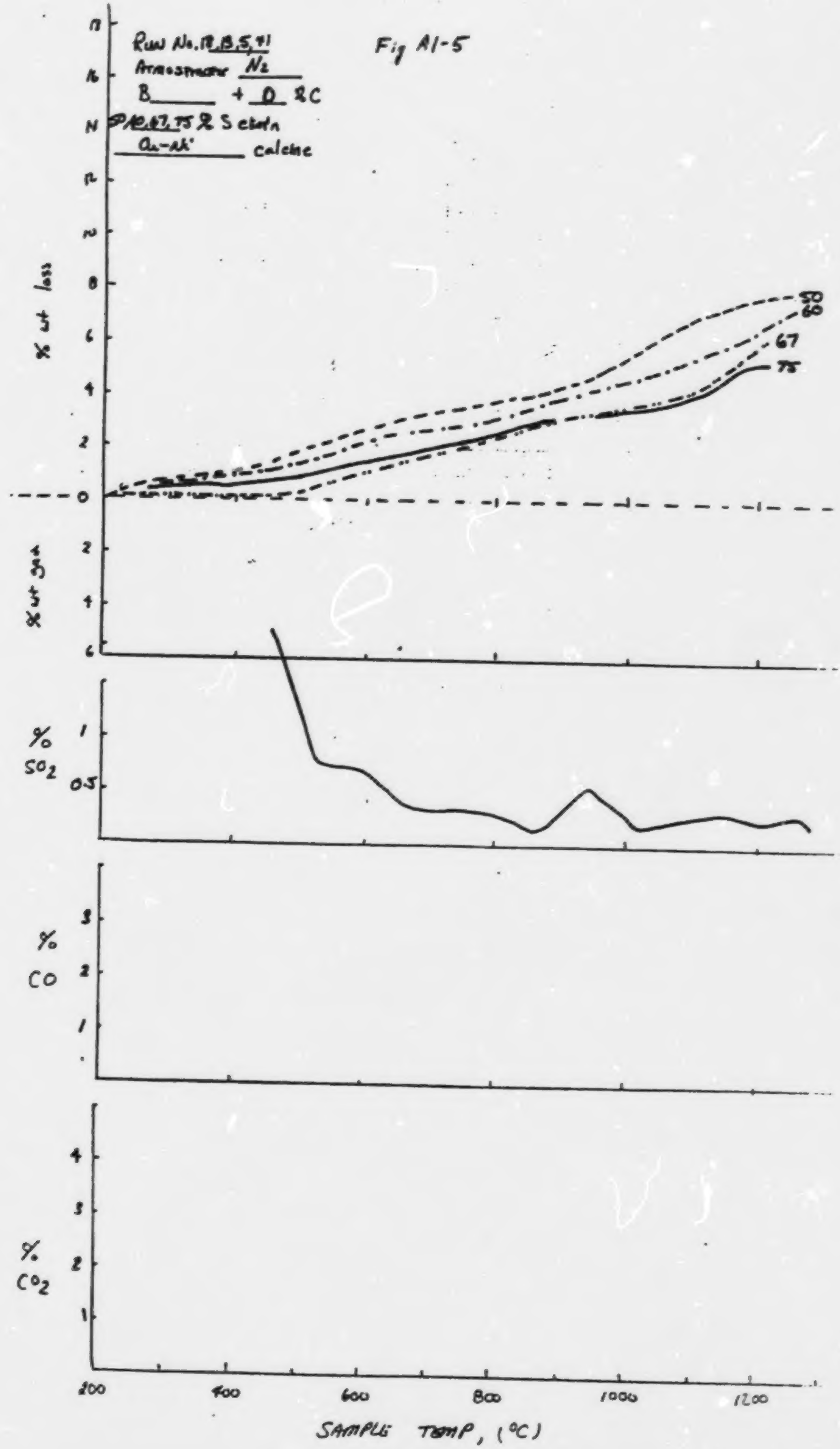
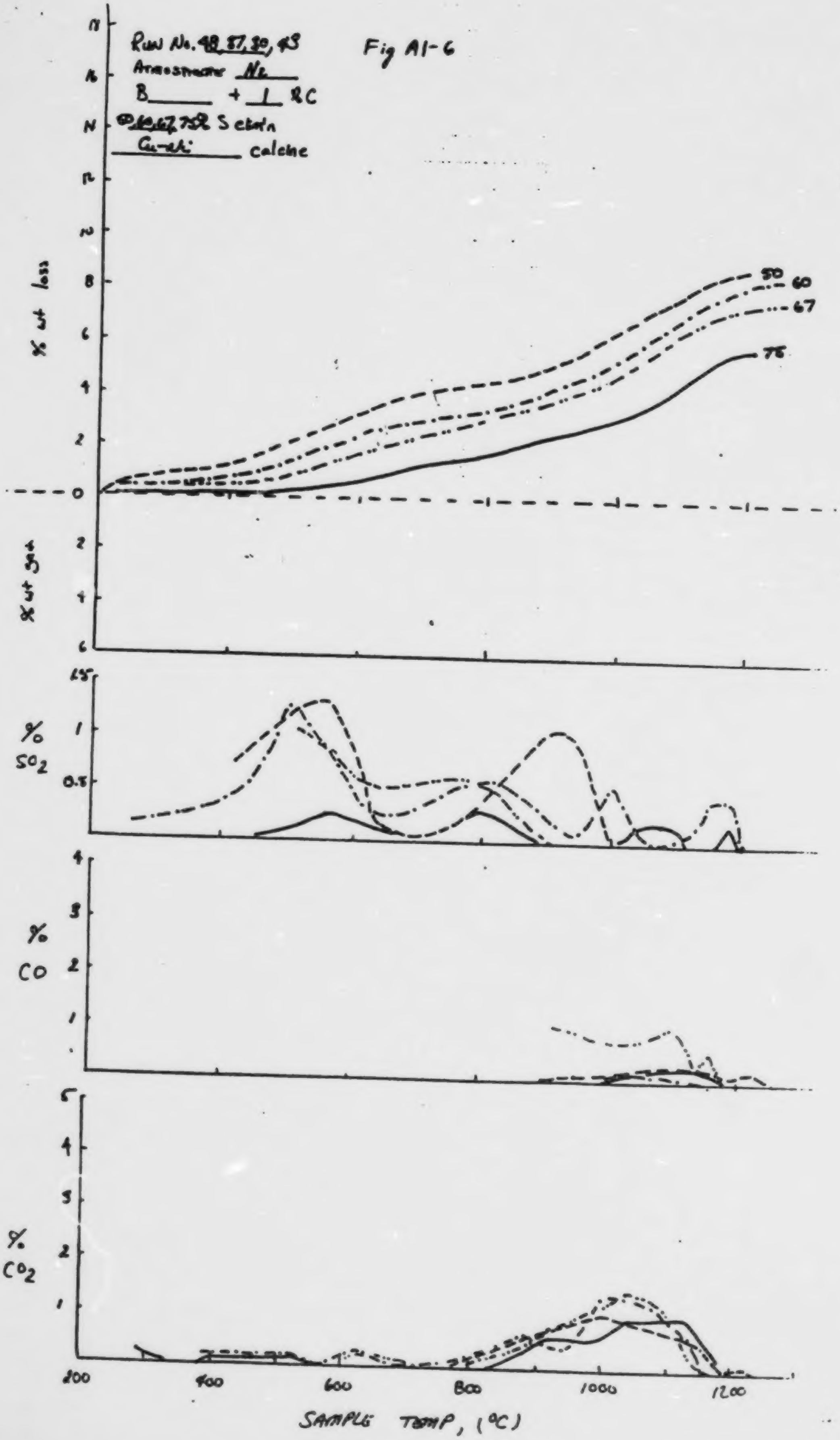
Run No. 12, 13, 5, 41
Atmosphere N2
B ____ + D &C
50, 67, 75 % S chtn
Al-Al' calcine
% wt loss
% wt gain
17
16
14
12
10
8
6
4
2
0
2
4
6
50
60
67
75
% SO2
1
0.5
% CO
3
2
1
% CO2
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig A1-5

Fig A1-6


Run No. 48, 57, 80, 43
Atmosphere N2
B ____ + 1 RC
@ 50, 67, 75% S elimin
Cu-sh. ____ calcine
18
16
14
12
10
8
6
4
2
0
2
4
6
% wt loss
% wt gain
50
60
67
75
1.5
1
0.5
% SO2
4
3
2
1
% CO
5
4
3
2
1
% CO2
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

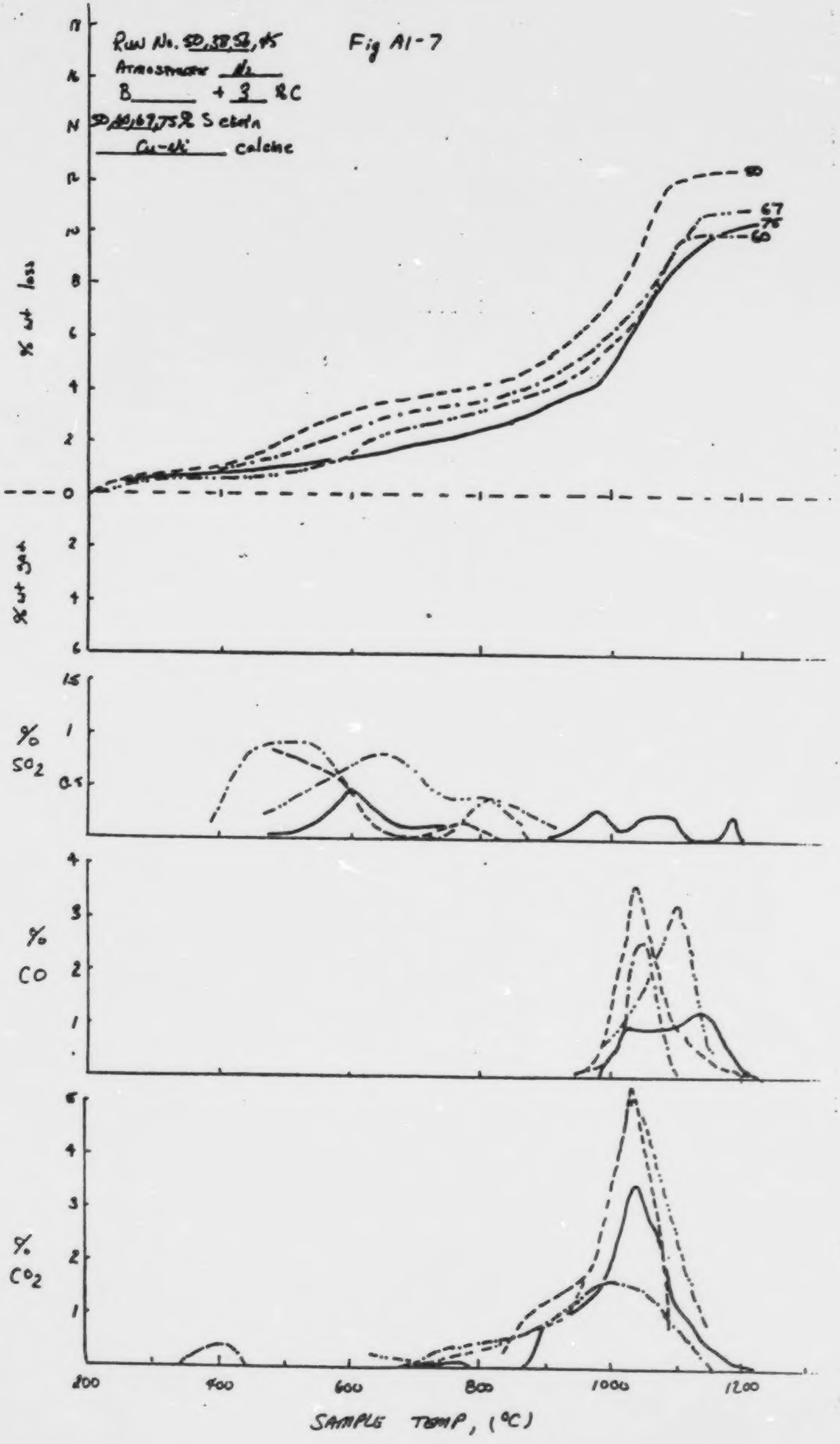
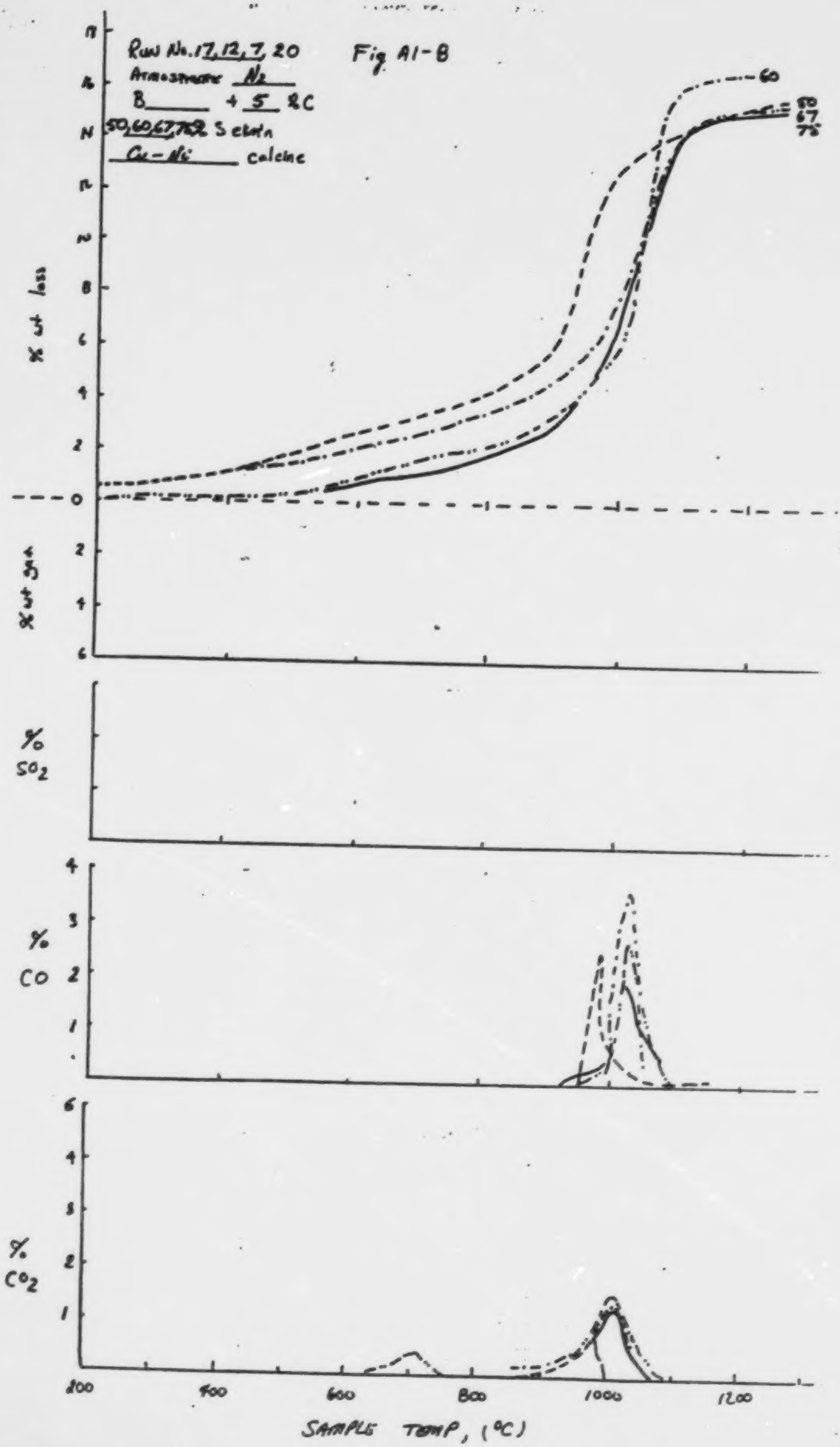


Fig A1-7

Run No. 50,38,56,45
Atmosphere N2
B ___ + 3 %C
50,60,67,75% S cbtn
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
80
67
75
60
% SO2
1.5
1
0.5
% CO
4
3
2
1
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig A1-B

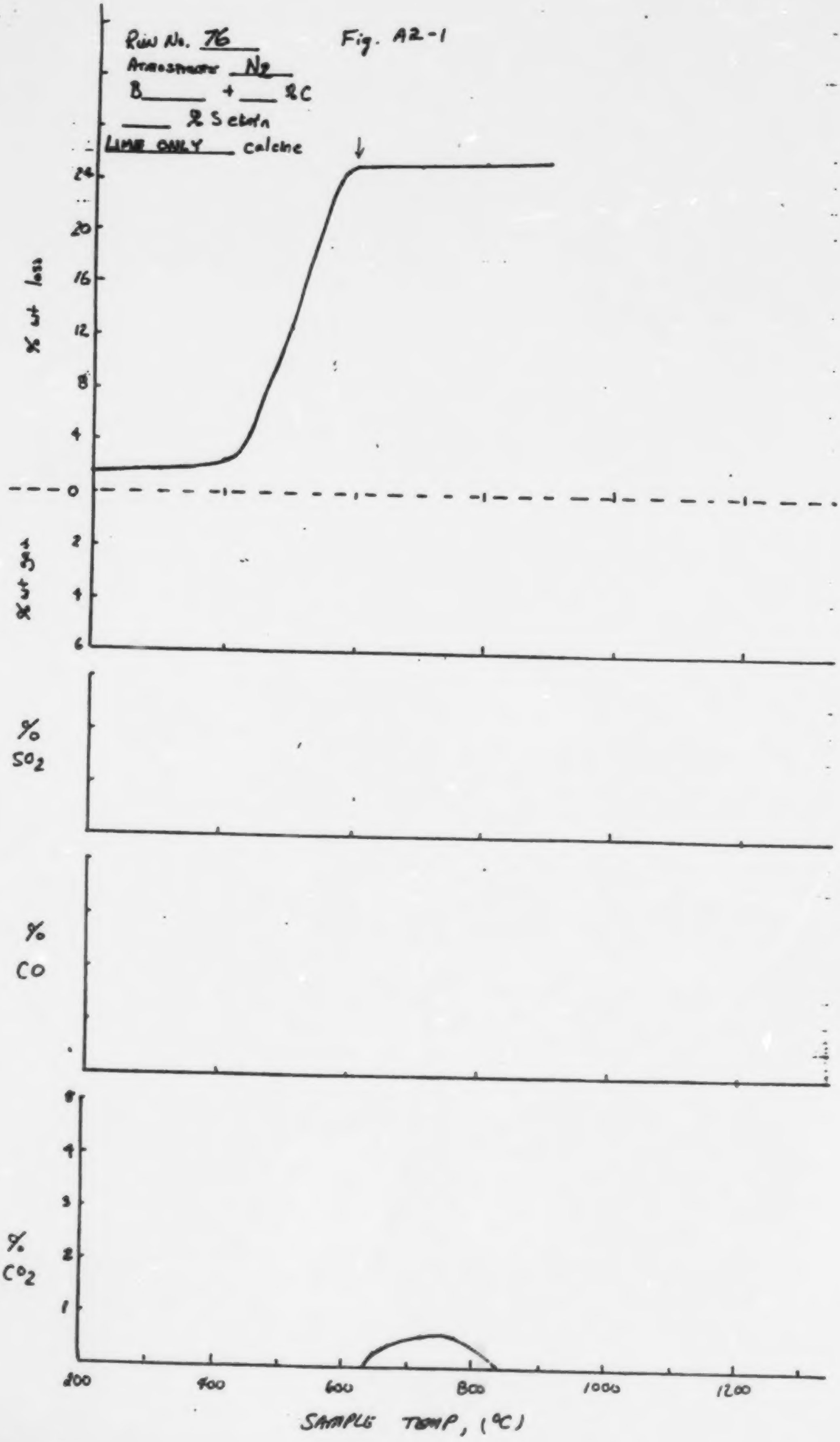

Run No. 17, 12, 7, 20
Atmosphere N2
B ____ + 5 %C
50, 60, 67, 75 % S elmtn
Cu-Ni calcine
% wt loss
18
16
14
12
10
8
6
4
2
0
% wt gain
2
4
6
60
50
67
75
%
SO2
%
CO
4
3
2
1
%
CO2
6
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

APPENDIX 2

GRAPHICAL RESULTS FOR TEST SERIES 2: NITROGEN ATMOSPHERE, 0-15% LIME ADDITION

Fig. No.	% Roast	% Coke	% Lime
A2-1		Lime only	
A2-2	60	5	0-15
A2-3	67	5	0-15
A2-4	60	5	0-15] adjusted for
A2-5	67	5	0-15] moisture in lime

Fig. A2-1



Run No. 76
Atmosphere N2
B___ + ___ %C
___ % Soln
LIME ONLY calcine
% wt loss
24
20
16
12
8
4
0
2
4
6
% wt gn
%
SO2
%
CO
%
CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

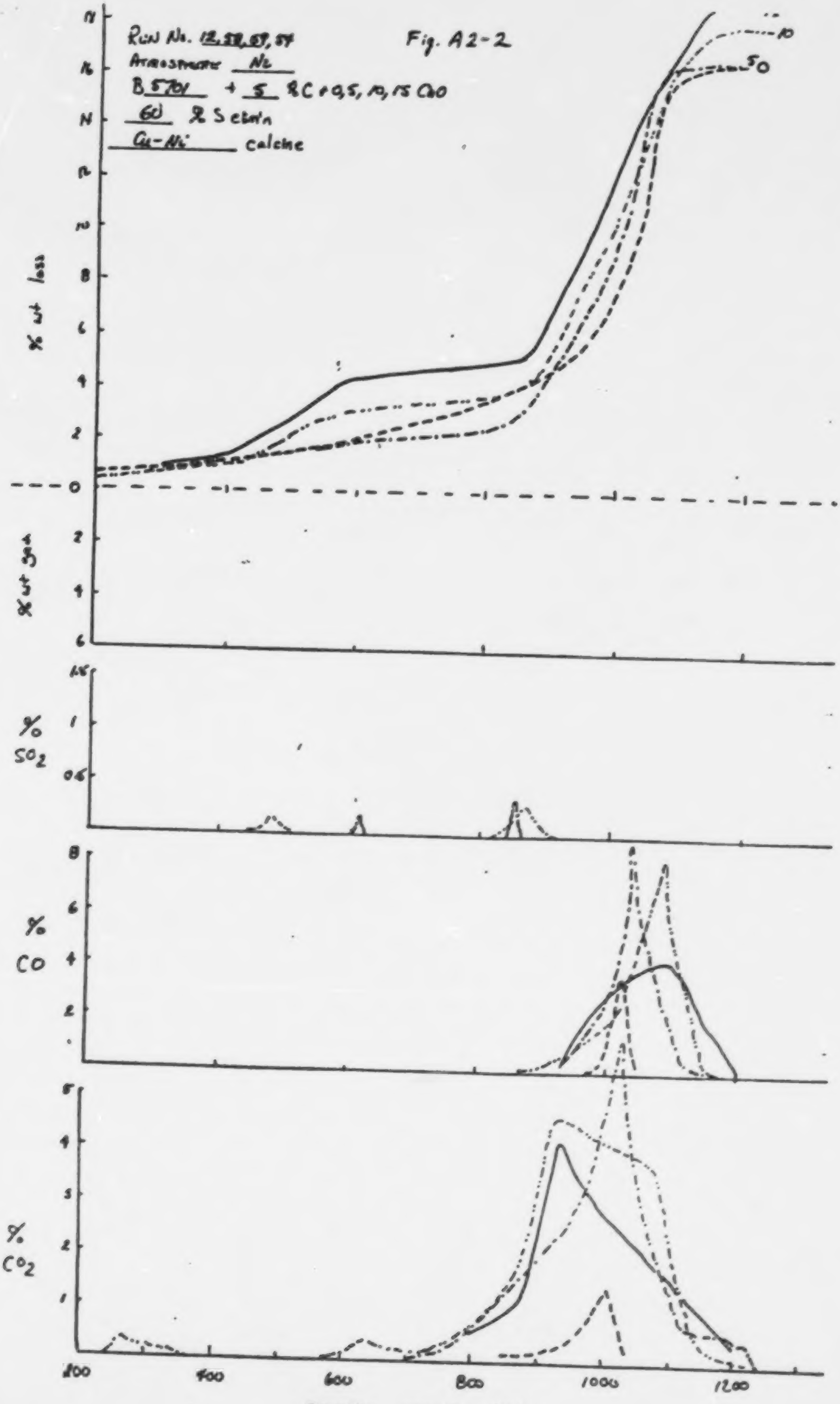


Fig. A2-2

Run No. 12, 58, 57, 59
Atmosphere N2
B 5701 + 5 %C + 0,5,10,15 CaO
60 % S elim'n
Cu-Ni calcine
18
16
14
12
10
8
6
4
2
0
2
4
6
% wt loss
% wt gain
10
5
0
1.5
1
0.5
% SO2
8
6
4
2
% CO
5
4
3
2
1
% CO2
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

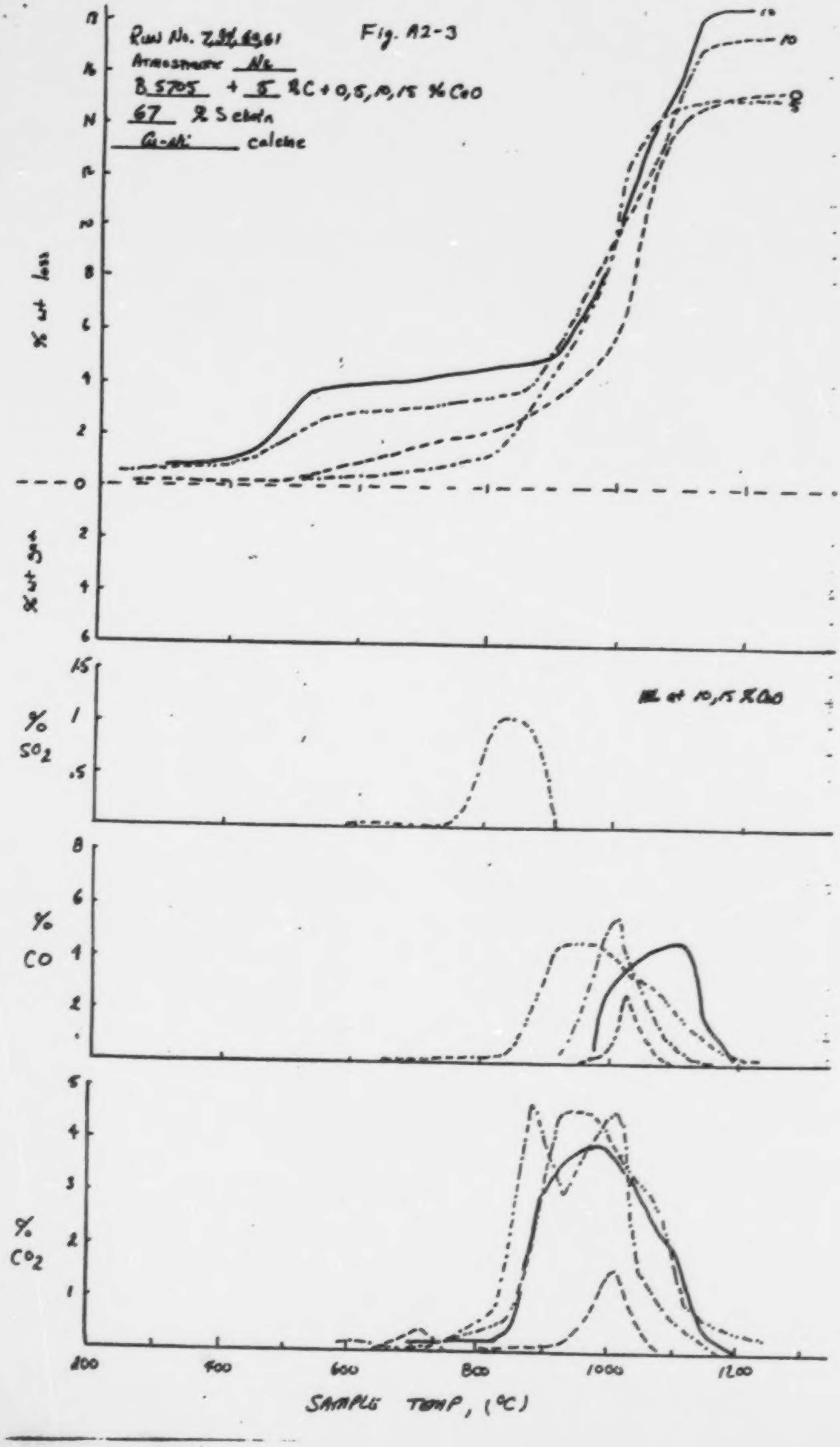

Run No. Z-86-8361
Atmosphere N2
B 5705 + 5 % C + 0, 5, 10, 15 % CaO
67 % S elutn
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
15
10
0
5
% SO2
1.5
1
.5
at 10, 15 % CaO
% CO
8
6
4
2
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig. A2-3

Fig. A2-4

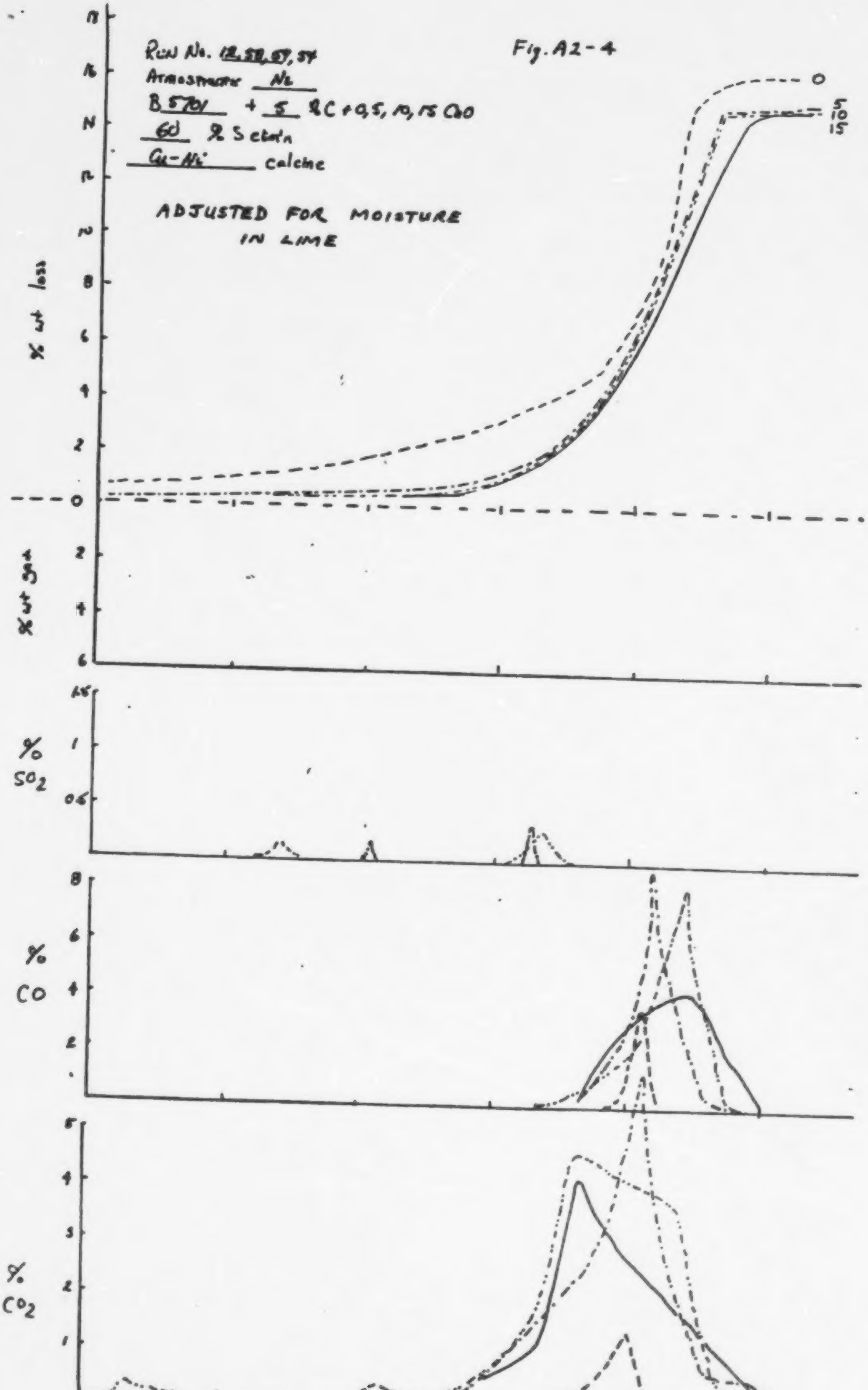
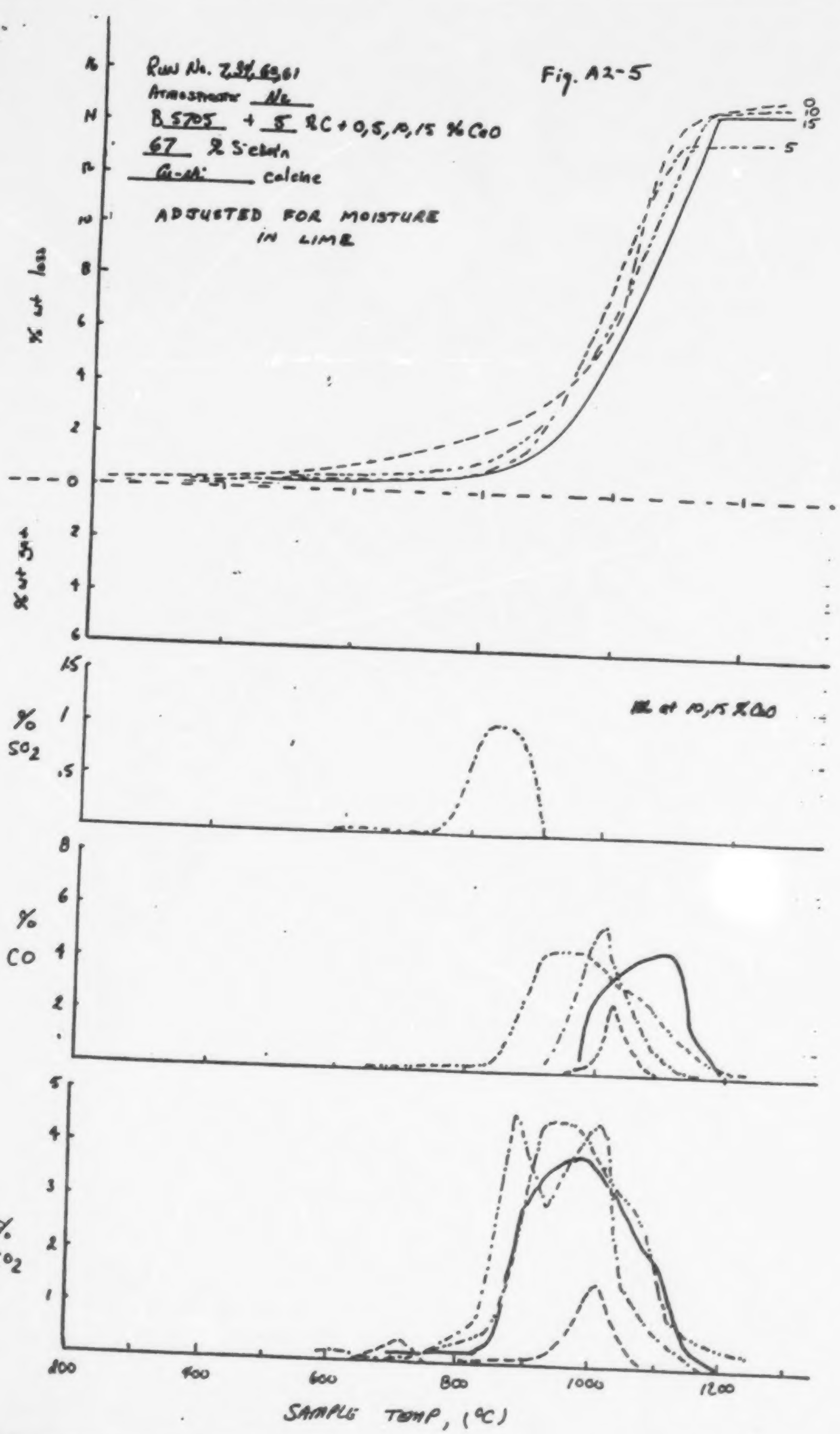

Run No. 12, 58, 57, 54
Atmosphere N2
B 5701 + 5 % C + 0, 5, 10, 15 CaO
60 % S elutn
Cu-Ni calcine
ADJUSTED FOR MOISTURE IN LIME
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
0
5
10
15
% SO2
1.5
1
0.5
% CO
8
6
4
2
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig. A2-5


Run No. 234,6361
Atmosphere N2
B5705 + 5 % C + 0,5,10,15 % CaO
67 % S-chain
Ca-Al calcine
ADJUSTED FOR MOISTURE IN LIME
% wt loss
% wt gain
16
14
12
10
8
6
4
2
0
2
4
6
0
10
15
5
% SO2
1.5
1
.5
[illegible] at 10,15 % CaO
% CO
8
6
4
2
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

APPENDIX 3

GRAPHICAL RESULTS FOR TEST SERIES 3: AIR ATMOSPHERE

Fig. No.	% Roast of Calcine	% Coke Addition
A3-1	Coke only	
A3-2	50	0-5
A3-3	60	0-5
A3-4	67	0-5
A3-5	75	0-5
A3-6	50-75	0
A3-7	50-75	1
A3-8	50-75	3
A3-9	50-75	5

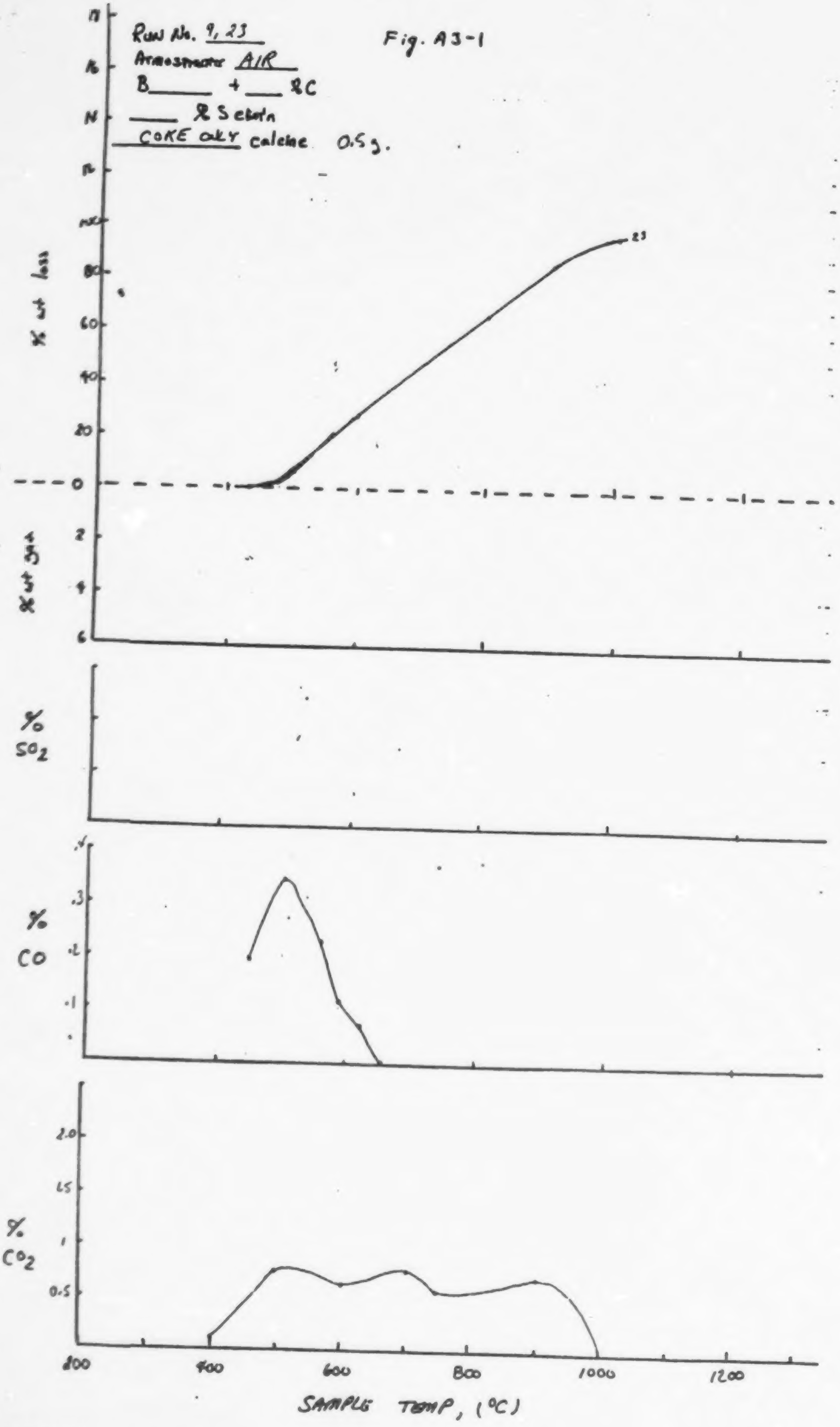

Run No. 9, 23
Atmosphere AIR
B______ + ___ %C
_____ % S eblotn
COKE ONLY calcine 0.5 g.
18
16
14
12
100
80
60
40
20
0
2
4
6
% wt loss
% wt gn
23
%
SO2
.4
.3
.2
.1
%
CO
2.0
1.5
1
0.5
%
CO2
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig. A3-1

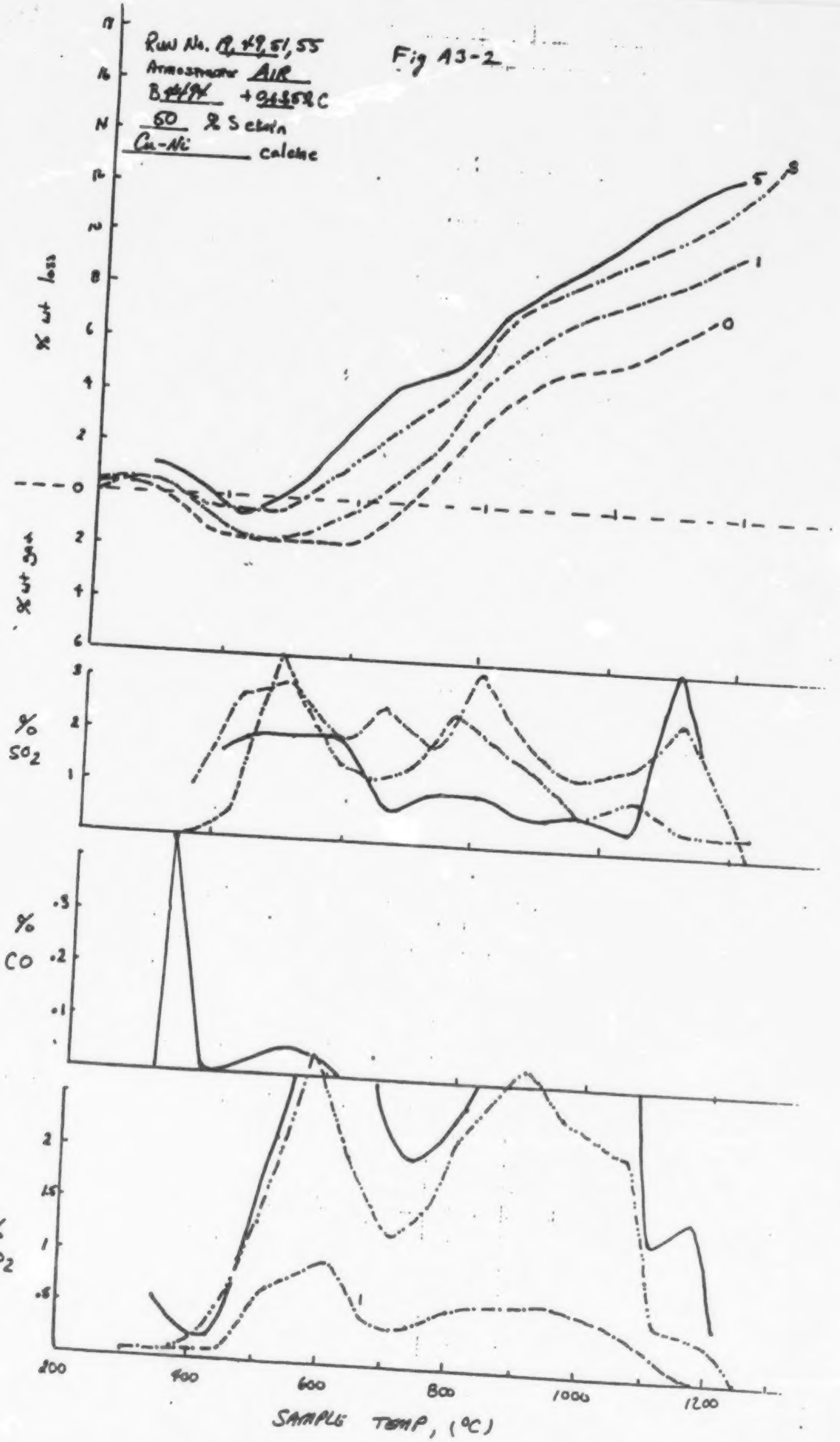


Fig A3-2

Run No. 19,49,51,55
Atmosphere AIR
B 44/94 + 9.1-3.5 % C
50 % S elim
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
5
3
1
0
% SO2
3
2
1
% CO
.3
.2
.1
% CO2
2
1.5
1
.5
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

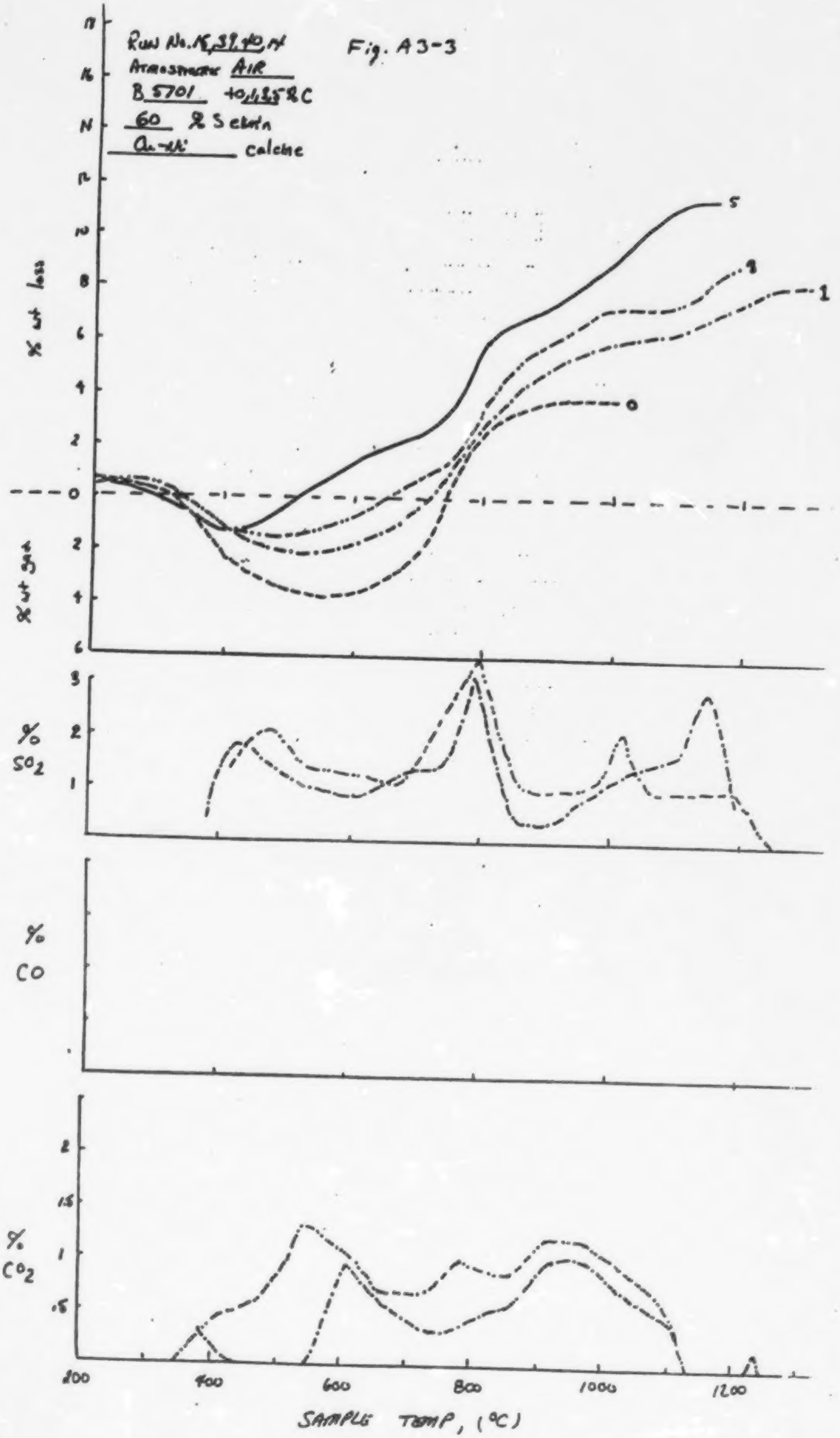
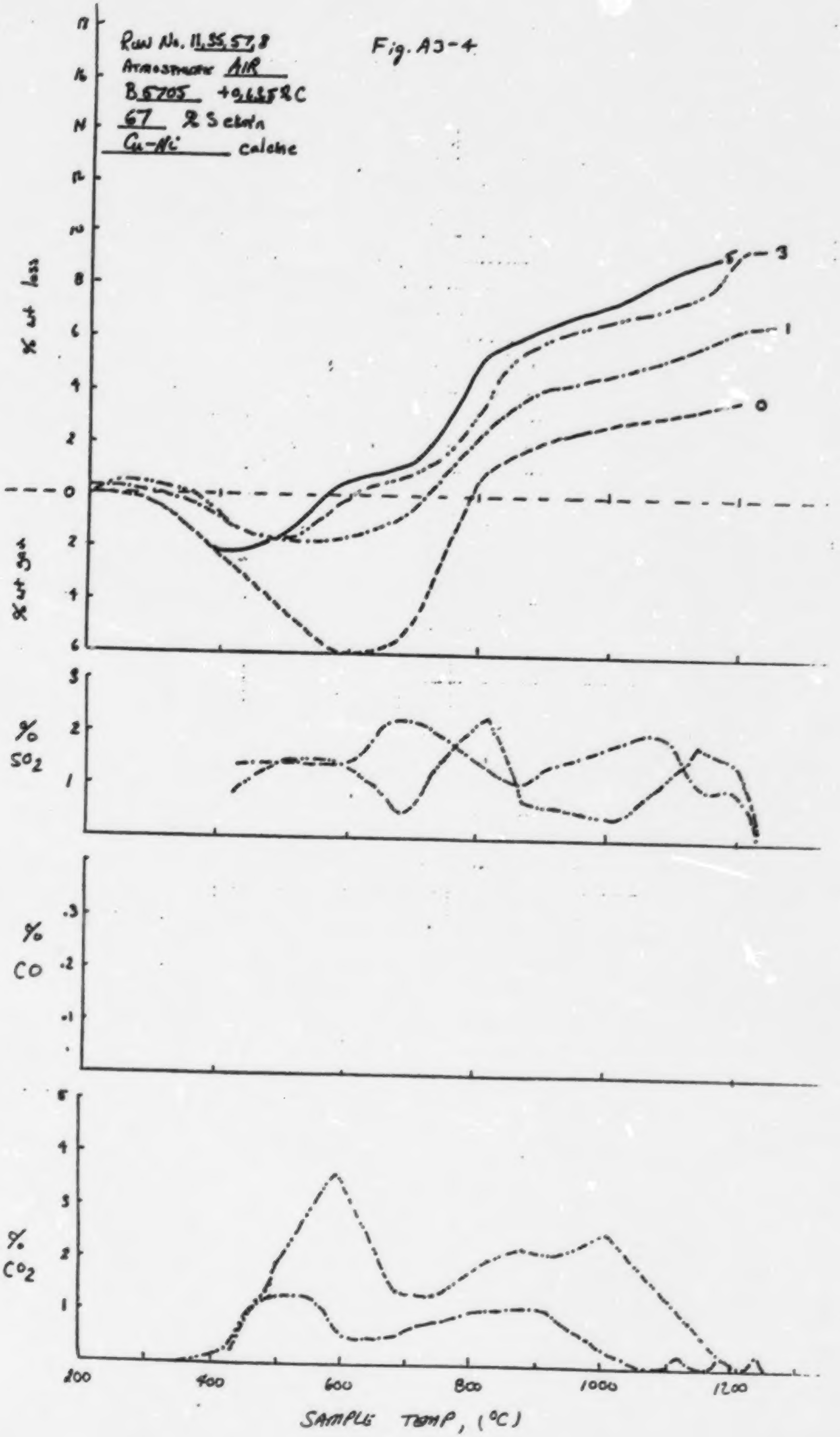


Fig. A3-3

Run No. 15, 39, 40, 41
Atmosphere AIR
B 5701 +0, 1, 3, 5 % C
60 % S ebtn
Ca-rich calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
5
3
1
0
% SO2
3
2
1
% CO
% CO2
2
1.5
1
.5
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)



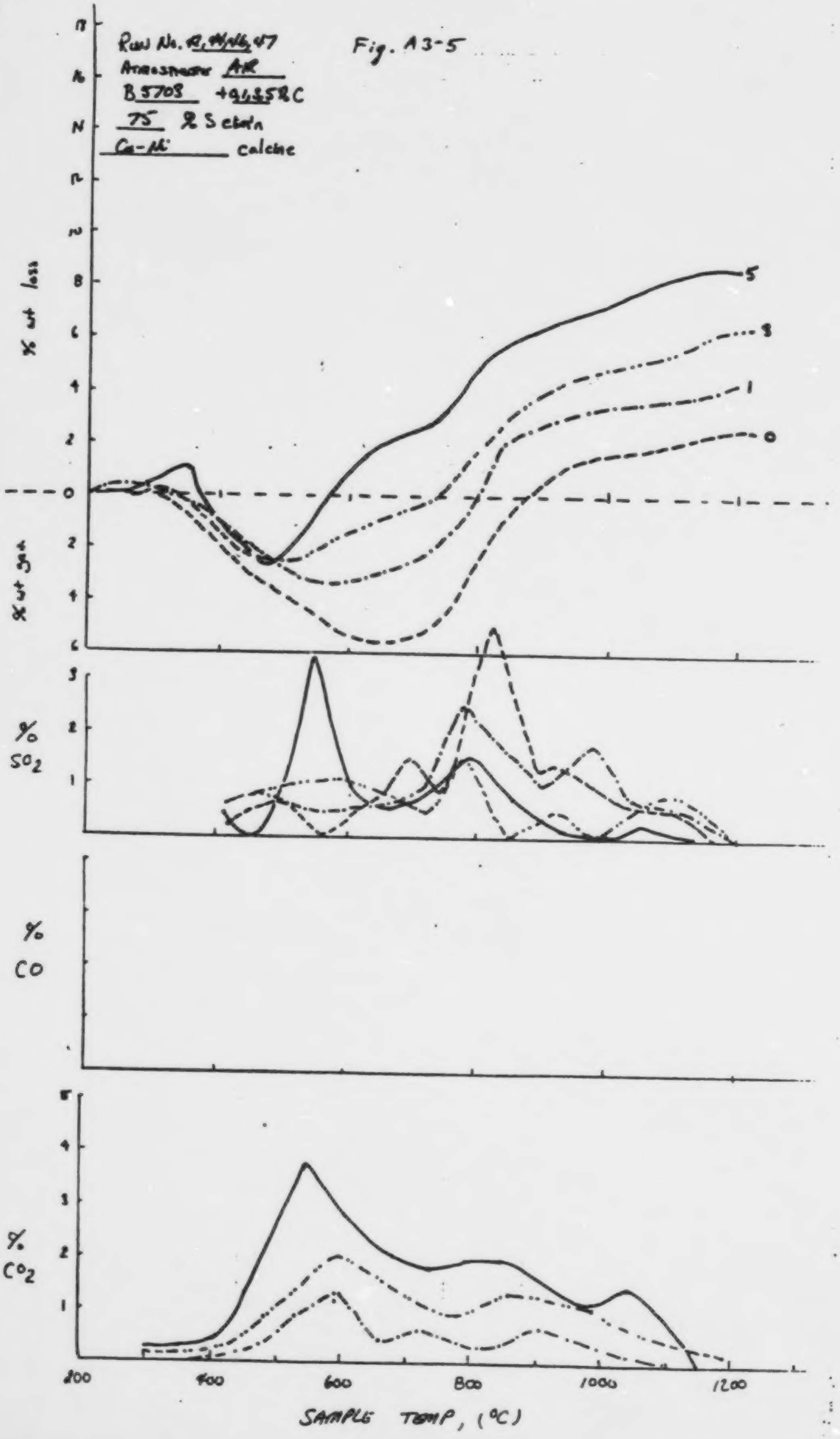
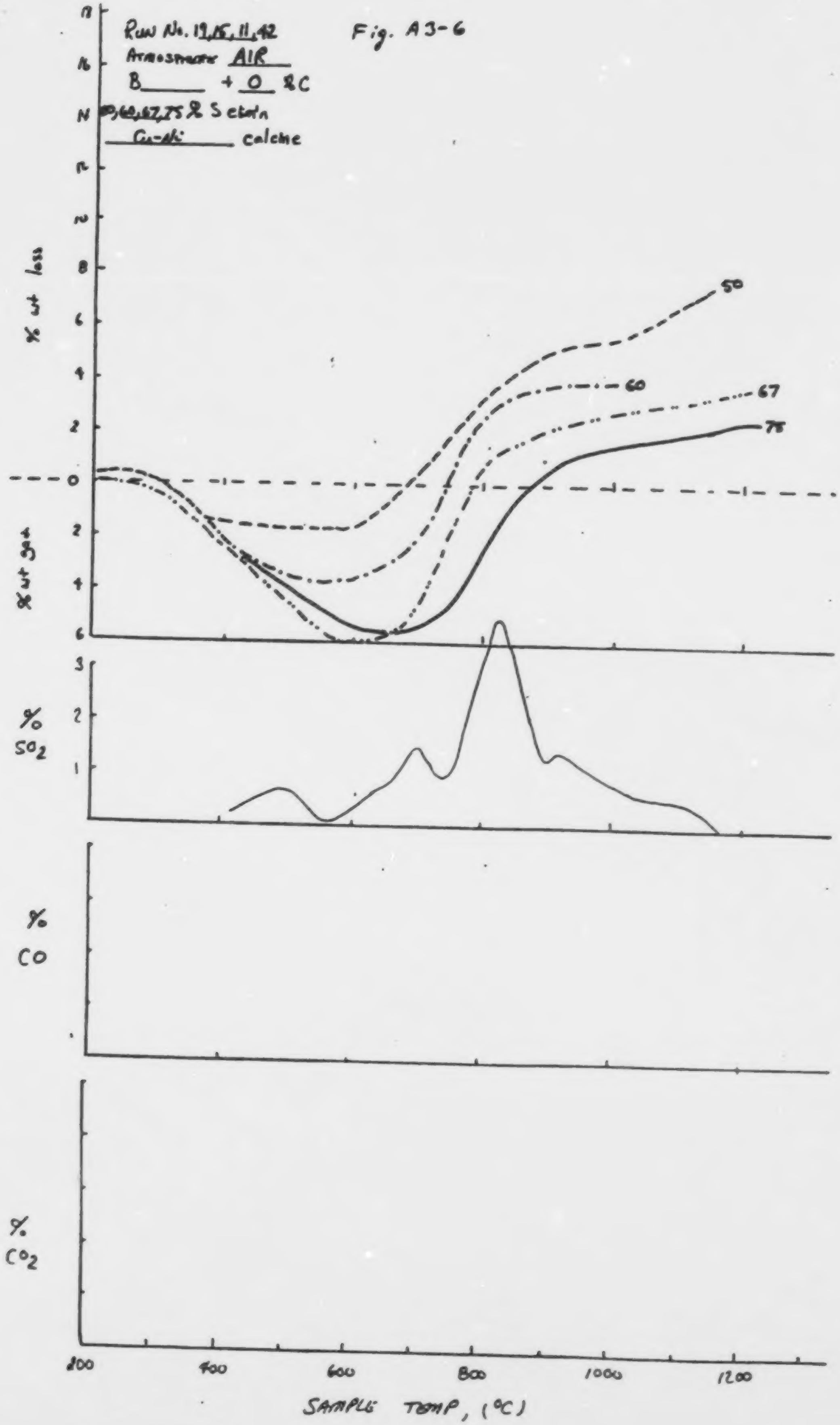


Fig. A3-5

Run No. [illegible] 47
Atmosphere AIR
B 5703 +9.35 % C
75 % S elimin
Cu-Ni calcine
18
16
14
12
10
8
6
4
2
0
2
4
6
% wt loss
% wt gain
5
3
1
0
3
2
1
% SO2
% CO
5
4
3
2
1
% CO2
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig. A3-6


Run No. 19, 15, 11, 42
Atmosphere AIR
B + 0 % C
50, 60, 67, 75 % S cktn
Cu-Ni calcine
18
16
14
12
10
8
6
4
2
0
2
4
6
% wt loss
% wt gain
50
60
67
75
3
2
1
% SO2
% CO
% CO2
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

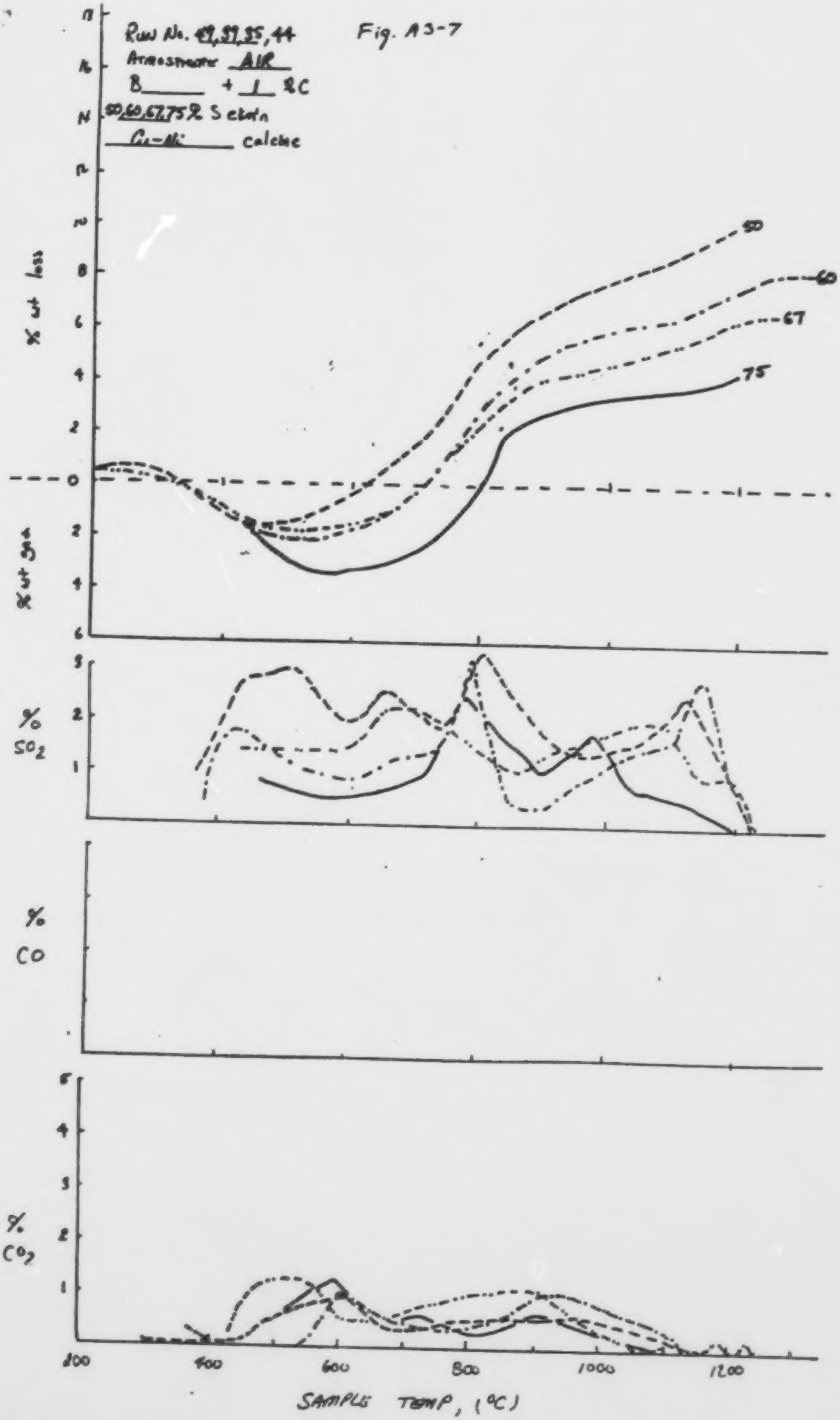


Fig. A3-7

Run No. 49,51,55,44
Atmosphere AIR
B ___ + 1 %C
50,60,67,75% S elutn
Cu-Ni calcine
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
50
60
67
75
%
SO2
3
2
1
%
CO
%
CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

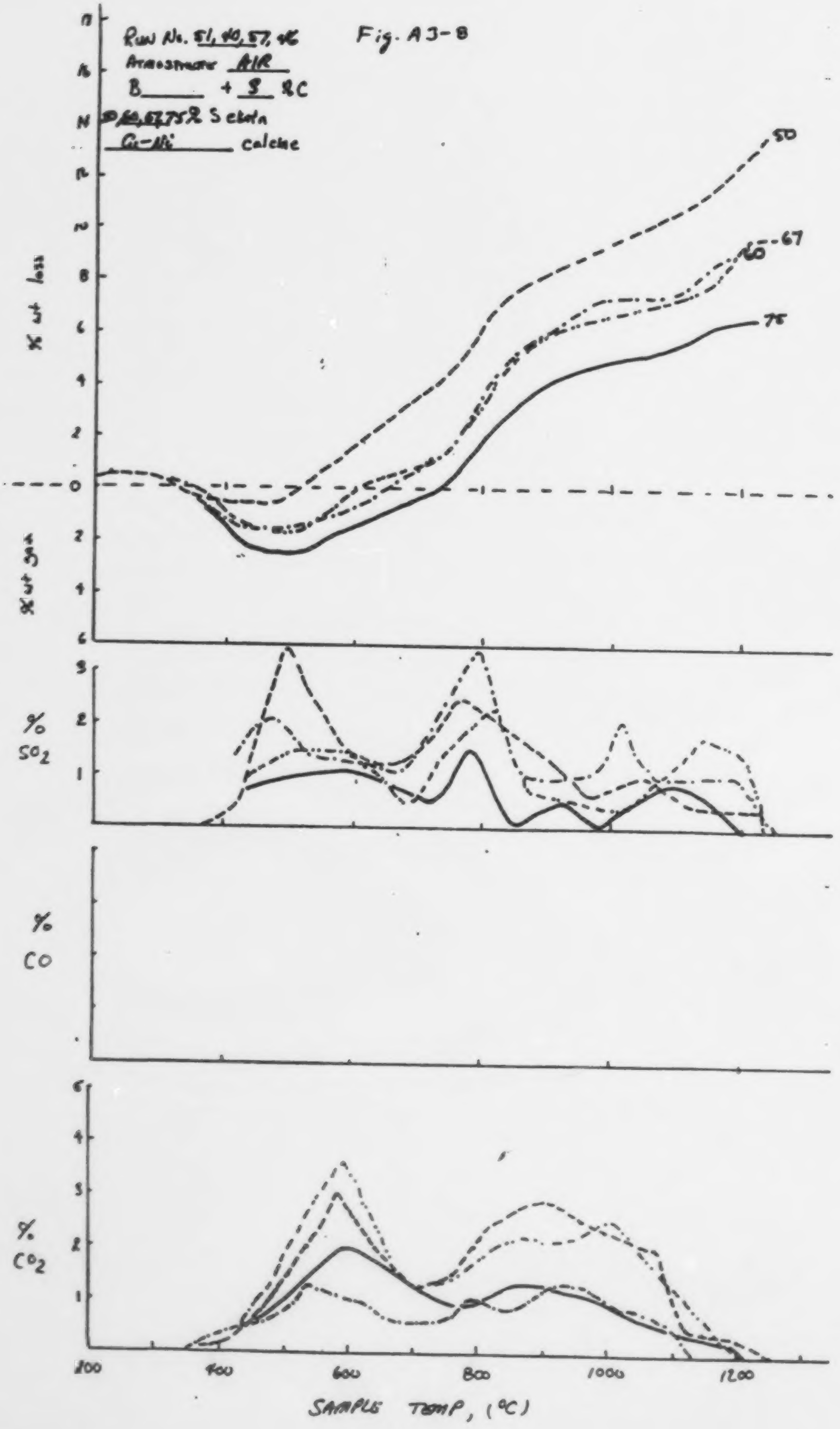
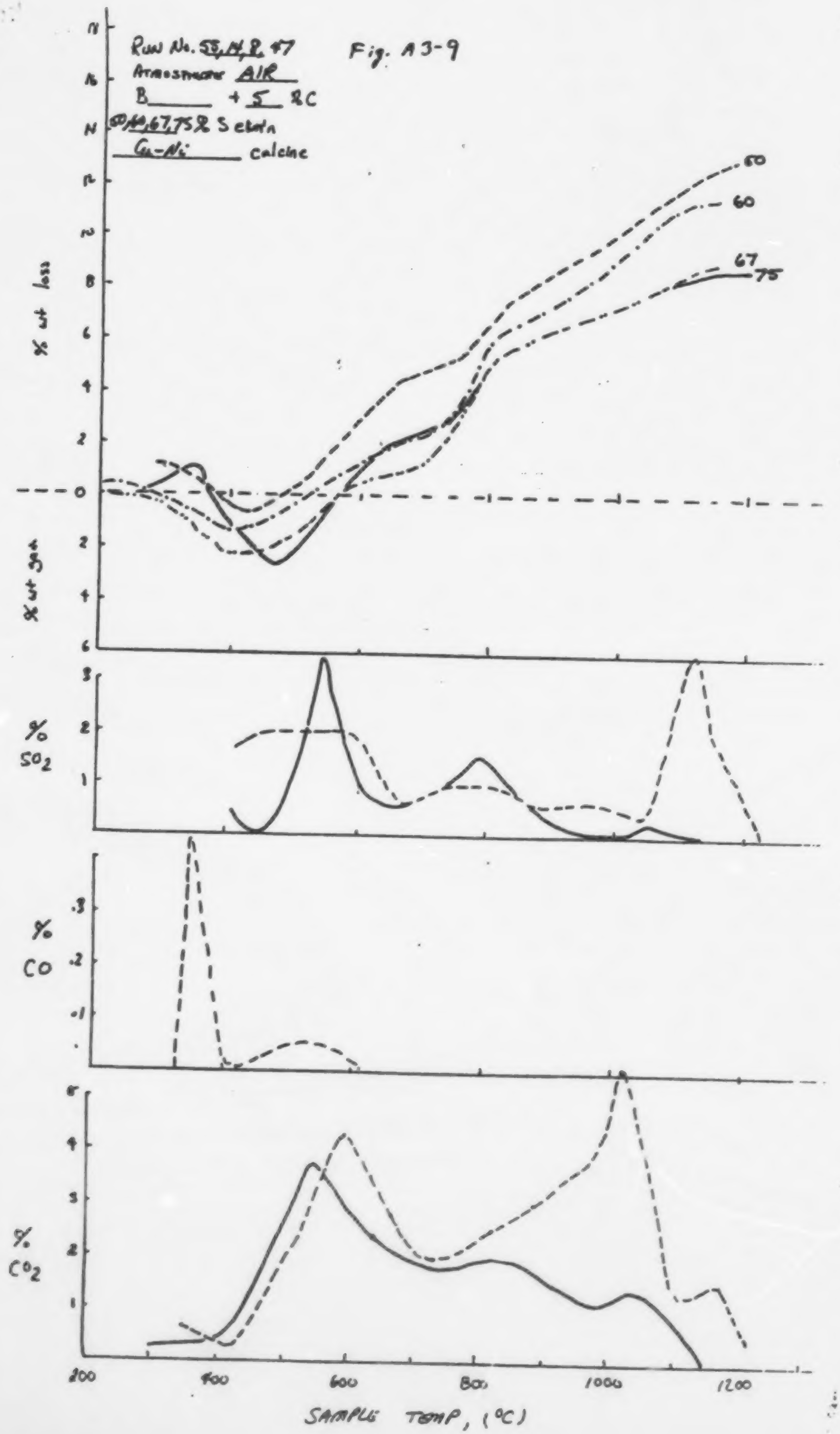

Run No. 51, 40, 57, 46
Atmosphere AIR
B ___ + 8 %C
50,60,67,75 % S ebdn
Cu-Ni calcine
50
67
60
75
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
%
SO2
3
2
1
%
CO
%
CO2
6
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

Fig. A3-8

Fig. A3-9



Run No. 55, 14, 8, 47
Atmosphere AIR
B + 5 %C
50, 60, 67, 75 % S cbstn
Cu-Ni calcine
50
60
67
75
% wt loss
% wt gain
18
16
14
12
10
8
6
4
2
0
2
4
6
% SO2
3
2
1
% CO
.3
.2
.1
% CO2
5
4
3
2
1
200
400
600
800
1000
1200
SAMPLE TEMP, (°C)

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A thesis submitted in conformity with the requirements
for the Degree of Master of Applied Science
in the University of Toronto

DENSITIES OF MOLTEN COPPER-NICKEL MATTES

BY

JOHN NICHOLAS HRYN

Department of Metallurgy and Materials Science

CONTRACT SERIAL NUMBER OSQ83-00195

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To Develop a Clean Smelting Process for Highly Roasted Copper-Nickel Calcines

93pp

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Project: 82-600

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TABLE OF CONTENTS

PAGE

Acknowledgements iii

List of Figures and Tables vi

Abstract viii

Introduction 1

Literature Survey 4

- i) Capillary Rise Technique 4
- ii) U-tube Technique 7
- iii) Sessile Drop Technique 10
- iv) Maximum Bubble Pressure Technique 12
- v) Archimedean Technique 14
- vi) Analyses of Techniques 17

Outline of Research Program 18

Experimental 24

- i) Apparatus 24
  - a) Furnace 24
  - b) Power Considerations 27
  - c) Lower Drive Assembly 28
  - d) Upper Drive Assembly 30
  - e) Alumina Bobs 31
  - f) Gas Train 32
- ii) Specimen Preparation 35
- iii) Technique 40
  - a) Derivation of Equations 40
  - b) Procedure 45

TABLE OF CONTENTS (...continued) PAGE

Results 49

Discussion 58

i) Technique 58

a) Volume of Alumina Bobs 58
b) Measurements 61
c) Errors in the Measurements 64

ii) Specimen Related 66

a) Initial Compositions 66
b) Changes in Matte Composition 67
c) Sampling Methods 69

iii) Matte Density as a Function of Temperature and Composition 71

Conclusions 73

References 74

Appendicies 76

Appendix A - Initial Compositions of B-series Specimens 77

Appendix B - Target Compositions of C-series Specimens 78

Appendix C - Final Assays of Matte Specimens 79

Appendix D - Raw Data 80

LIST OF FIGURES AND TABLES

PAGE

Figure 1. Apparatus used by Bourgon et al. 5

Figure 2. Apparatus used by Travnichek and Chernomurov. 6

Figure 3. Apparatus used by Byerley and Takebe. 7

Figure 4. Sample of data obtained by Byerley and Takebe. 9

Figure 5. Apparatus used by Tokumoto et al. 10

Figure 6. Sketch of meridional section of sessile drop. 11

Figure 7. Apparatus used by Nagamori. 12

Figure 8. Apparatus used by Kaiura and Toguri. 15

Figure 9. The Cu-Ni-Fe-S composition diagram. 18

Figure 10. The (Cu+Ni)-Fe-S-O composition diagram. 19

Figure 11. Densities along the Cu_2S-Ni_3S_2 psuedo binary. 20

Figure 12. Oxygen solubility in converter mattes. 21

Figure 13. Oxygen content as a function of iron content in converter mattes. 21

Figure 14. The effect of oxygen on density. 22

Figure 15. Compositions of matte specimens investigated. 23

LIST OF FIGURES AND TABLES (...continued) PAGE

Figure 16. Apparatus. 26

Figure 17. Circuit diagram for furnace. 28

Figure 18. Bob and crucible arrangement. 33

Figure 19. Gas train. 34

Figure 20. Outline of the specimen preparation procedure. 36

Table 1. Normalized compositions and ratios of the first thirteen matte specimens. 49

Table 2. Normalized compositions and ratios of the seven synthesized matte specimens. 49

Figure 21a. Density data as a function of temperature. 51

Figure 21b. Density data as a function of temperature. 52

Table 3. Densities of the matte specimens. 53

Figure 22. Densities of the matte specimens at 1100°C. 55

Figure 23. Densities of the matte specimens at 1200°C. 56

Figure 24. Densities of the matte specimens at 1300°C. 57

Figure 25. Balance readout versus bob immersion depth. 62

ABSTRACT

A bottom-weighing Archimedean technique employing twin alumina bobs was used to determine the densities of twenty copper-nickel mattes. The specimens were held in a vertical tube Kanthal Super resistance furnace under a deoxidized argon atmosphere. The matte specimens were synthetically prepared to simulate typical industrial mattes. Copper/nickel mass ratios were held at 1:1 with the matte grade varying from 13% to 57% copper plus nickel. Oxygen was added to the mattes to correspond to an iron/oxygen mass ratio of 16:1, which is typical of industrial mattes. Densities were determined in the temperature range 1100 - 1300°C. Accuracy of the obtained density values were within 0.5%. An empirical equation relating the density of mattes to their composition and temperature was developed, and is given below:

$$\begin{aligned}\text{Density}[\text{g/mL}] = {} & 6.532 - 0.0856 \cdot \text{mass\% S} \\ & + 0.0097 \cdot \text{mass\% (Cu + Ni)} \\ & + 0.00049 \cdot (1200 - T[\text{C}^{\circ}]).\end{aligned}$$

RÉSUMÉ

La densité de vingt échantillons de mattes de cuivre et nickel a été déterminée par l'application du principe d'Archimède à un sytème de pesage par en bas, en opérant le déplacement au moyen d'une série de deux cylindres en alumine. Les échantillons reposaient sur un support, à l'intérieur d'un four à resistance Kanthal Super à tube vertical, dans une atmosphère désoxydée d'argon. Les échantillons de matte avaient été produits synthétiquement de façon à simuler les mattes industrielles typiques. Les proportions par masse cuivre/nickel étaient égales (1:1), tandis que la qualité de la matte variait de 13% à 57% (teneur combinée en cuivre et nickel). On a ajouté aux mattes de l'oxygène dans la proportion par masse fer/oxygène 16:1, proportion typique des mattes industrielles. Les densités ont été déterminées dans un milieu dont la température allait de 1100° à 1300° C. Les densités obtenues étaient exactes à 0,5 % près. L'équation empirique suivante, indiquant la densité des mattes par rapport à leur composition et leur température, a été établie:

$$\begin{aligned}\text{Densité [g/mL]} &= 6{,}532 - 0{,}0856 \times \text{masse \% S} \\ &+ 0{,}0097 \times \text{masse \% (Cu + Ni)} \\ &+ 0{,}00049 \times (1200 - \text{T[C°]})\end{aligned}$$

INTRODUCTION

This thesis describes the determination of the densities of molten copper-nickel mattes. Reliable density data are presently unavailable. In cooperation with Falconbridge Ltd., the densities of several synthetic copper-nickel mattes were measured over the temperature range 1100 - 1300°C. The compositions of the matte specimens were restricted to those that were considered to be most suited to the needs of the industry.

Volumes of liquids are difficult to measure due to surface and interfacial tension effects. This is the main reason that accurate density data are difficult to obtain. The determination of the densities of molten sulfides is further complicated by the high temperatures required and the necessity to control the atmosphere, since sulfur is readily oxidized to various sulfur oxides which can escape as gas and thereby change the composition of the matte specimen.

There are practical and theoretical reasons as to why density data of molten mattes are important. Density data are required in the analyses of reaction rates that occur in sulfide smelting and converting processes. For example, they can be used to establish the concentration of the melt in terms of unit volume. This can then be used to formulate natural convective effects that arise from density changes resulting from metallurgical reactions.

Knowledge of densities could also lead to a better understanding of the phenomena which give rise to the presence of a solid magnetite phase in smelting and converting vessels. Should a solid magnetite phase form, density data can help predict its location. For example, in higher matte grades which have higher densities than that of solid magnetite, magnetite will accumulate at the matte-slag interface where it can impede the reaction rate between the matte and slag. In lower matte grades with lower densities, magnetite will accumulate at the bottom of the vessel, where it can block tuyeres and restrict the flow of oxygen. By knowing the density of the matte, detection of magnetite is facilitated.

Mass balances in pyrometallurgical plants have always been difficult to determine, yet they are important in assessing the economics of the processes. One of the major difficulties occurs in the converter aisle. The quantity of matte converted is usually recorded by the number of ladles processed. Although the volume of each ladle is known, the mass of matte in each ladle is usually estimated, since the density of the matte is unknown. Therefore, matte density data can also improve the accuracy of material balances especially in the converter aisle.

But apart from the practical value of density data in treating matte-slag separation and transport problems, the data may provide a basis for a better understanding of the structure and bonding of molten mattes, especially when combined with data on other physical properties, such as electrical conductance, surface tension and viscosity. In that case, molar volumes, which are derived from density-composition relations, will be required. For example, metal-sulfur atomic bonding is considered to be somewhere between metallic and ionic, depending on composition and probably other variables. The radius of the S^{2-} anion was reported as 0.184 nm as compared to 0.104 nm for a singly bonded covalent sulfur atom. Without taking other atomic interactions into account, it could be argued that the partial molar volume of sulfur is larger when it is more ionic. In this way, density data, when converted to molar volumes, can help resolve the structure of these sulfide melts.

LITERATURE SURVEY

A literature survey extending back 30 years revealed that only a handful of papers have been published on the densities of molten mattes. Five methods have been used to measure matte densities: capillary rise technique, U-tube technique, sessile drop technique, maximum bubble technique, and an Archimedean technique. Each of these methods has its own advantages and disadvantages, but some are clearly superior to others. A brief summary of each technique will demonstrate this.

i) Capillary Rise Technique

In the late 1950's, Bourgon et al(1) measured the density of copper-iron sulfides over a temperature range from 1200 - 1400°C. The apparatus they used is shown in Figure 1.

The molten matte sits in an alundum crucible in an induction furnace under a helium atmosphere. A silica tube is placed into the matte. The other end of the silica tube leads to a manometer which contains silicone oil. As the furnace becomes pressurized with helium, matte is forced up the silica tube and causes a pressure change across the manometer. The height of the matte column is determined by

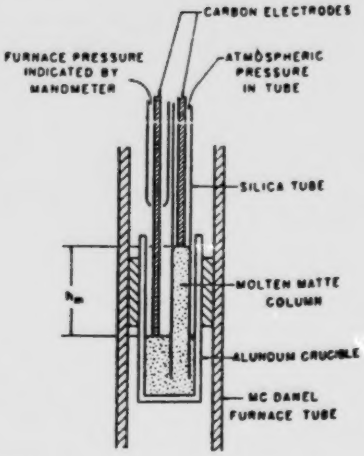

CARBON ELECTRODES
FURNACE PRESSURE INDICATED BY MANOMETER
ATMOSPHERIC PRESSURE IN TUBE
SILICA TUBE
h_m
MOLTEN MATTE COLUMN
ALUNDUM CRUCIBLE
MC DANEL FURNACE TUBE

Figure 1. Apparatus used by Bourgon et al.

moving two graphite rods to the surface of the matte and testing for completion of a circuit, since molten sulfides are conductive. Because the graphite rods are of the same length, the height of the matte column can be measured from the difference in height of the ends of the graphite rods above the furnace. The density of the matte can then be determined by Equation 1, if the density and height of the silicone oil in the manometer are known.

$$D_m = D_s \times (h_s / h_m) \quad \text{.....1}$$

where D_m is the density of the matte

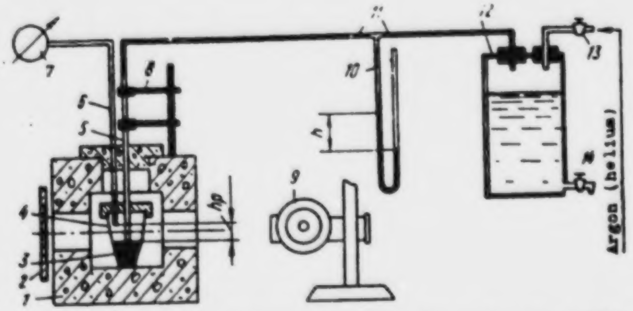
D_s is the density of the silicone oil

h_m is the height of the matte column

and h_s is the height of the silicone oil

The major disadvantage with this technique is the uncertainty in the position of the matte surface. This is due to fluctuations of the surface combined with an interfacial tension effect between the graphite and sulfide. Bourgon et al estimate their error at 2%.

Travnichek and Chernomurov(2), 1973, improved this technique by using x-rays to determine the position of the matte surface, both in the crucible and in the capillary. Their apparatus is shown in Figure 2.



Layout of an installation used to measure melt density:
1 - high-temperature furnace; 2 - x-ray film; 3 - melt; 4 - alundum crucible with cover; 5 - quartz or alundum capillary tube; 6 - thermocouple; 7 - potentiometer; 8 - guides; 9 - type RUP-200 x-ray flaw-detector; 10- water-pressure gauge; 11 - vacuum rubber hose; 12 - container; 13, 14 - taps.

Figure 2. Apparatus used by Travnichek and Chernomurov.

Density measurements were made for Cu_2S, Ni_3S_2, and FeS at temperatures from 1200 - 1400°C. Their data are good and their error is estimated at 0.2%. Unfortunately, the exact compositions of their sulfide specimens were not reported.

ii) U-tube Technique

Byerley and Takebe(3), 1971, used a so-called U-tube method which is a variation of the capillary rise technique. Their apparatus is shown in Figure 3.

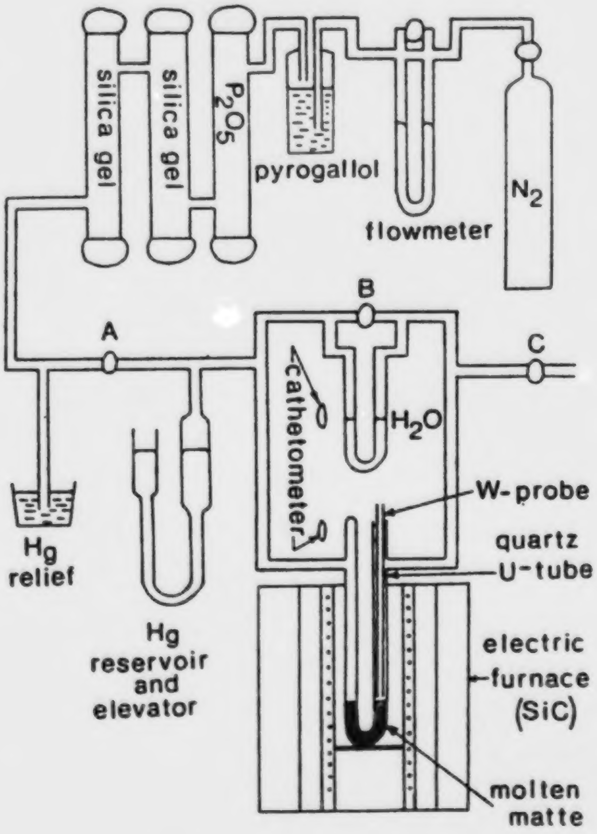

silica gel
silica gel
P_2O_5
pyrogallol
flowmeter
N_2
B
A
C
cathetometer
H_2O
W-probe
quartz
U-tube
Hg relief
Hg reservoir and elevator
electric furnace (SiC)
molten matte

Figure 3. Apparatus used by Byerley and Takebe.

The silica U-tube was fitted with a tungsten probe which could be set at a predetermined level. After purging, stopcocks A and C were closed, which isolated a control volume. Then, after closing stopcock B, the pressure in the left side of the apparatus was increased by raising the mercury level. When the matte rose to the preset level to complete a circuit of a lamp with the tungsten probe, the manometer level was recorded. The density could then be calculated using Equation 1, if substituting water for silicone oil.

This method apparently reduced the uncertainty of the matte column height by half because the probe is in contact with only one surface. But in order to determine the value of 'h_m' in Equation 1, the initial value of 'h' also had to be measured. It could not be calculated from the mass of the matte in the tube because the density was not known. Therefore, no real advantage is gained. This can explain why Byerley and Takebe's results are claimed to be reproducible to within 1%, but that the density values obtained are totally inconsistant with those of other authors, and do not show any logical trend. A sample of their data is shown in Figure 4.

Another problem inherent with the U-tube technique is the inability to adequately purge the atmosphere above the matte specimen. This occurs because of a pocket of stagnant gas above the matte. Any oxygen not purged from this gas will react with the sulfur in the matte and slightly change the specimen composition. But more important is the dissolution of oxygen into the matte phase

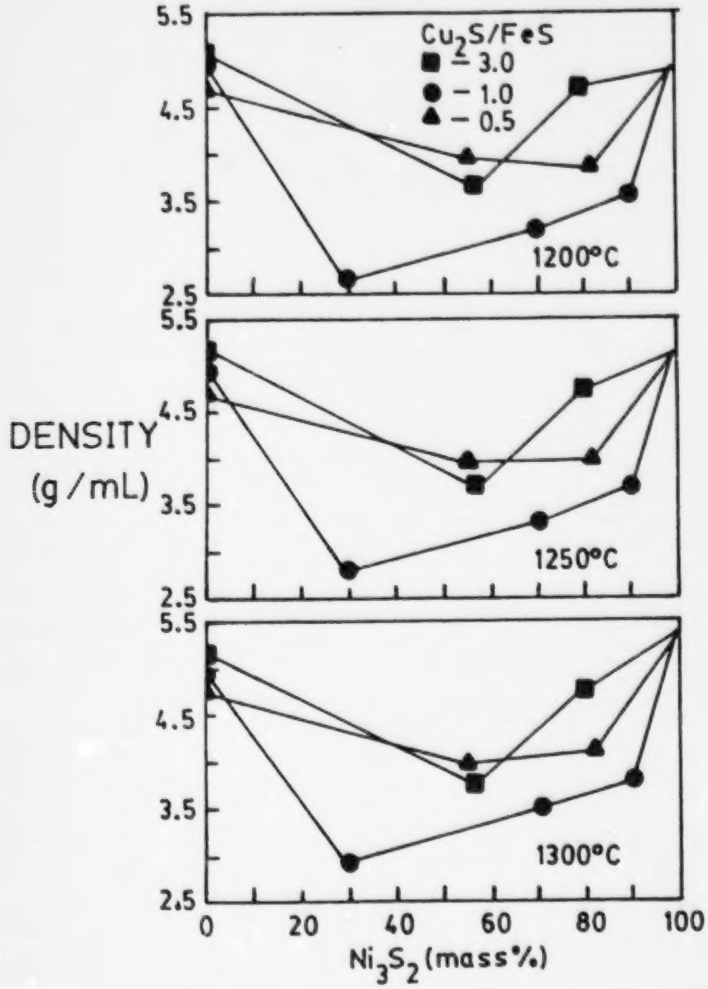


Figure 4. Sample of data obtained by Byerley and Takebe.

which increases the wettability of the silica by the matte. This will increase the error of the density value by further decreasing the apparent volume of the matte.

Azuma and Takebe(4), 1972, also used the U-tube technique to determine densities of molten copper mattes.

Their results also show scatter, but to a lesser degree than those of Byerley and Takebe. This is probably due to their improved purging technique. Nevertheless, the quality of their data seems to be inferior to those of authors who use other techniques to determine the densities of molten mattes.

iii) Sessile Drop Technique

Tokumoto et al(5), 1972, used the sessile drop method to measure the density and surface tension of copper mattes simultaneously. Their apparatus is shown in Figure 5.

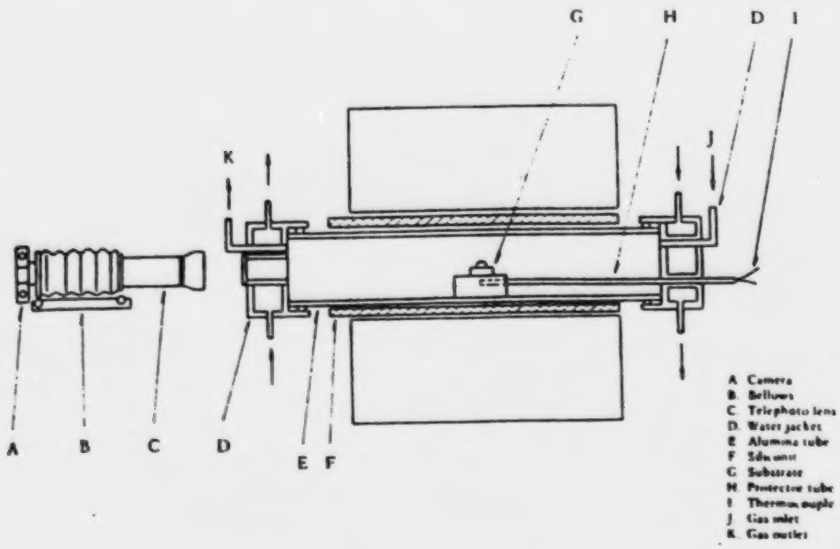

G
H
D
I
K
J
A
B
C
D
E
F
A Camera
B. Bellows
C. Telephoto lens
D. Water jacket
E Alumina tube
F Siliconit
G Substrate
H. Protector tube
I Thermocouple
J Gas inlet
K. Gas outlet

Figure 5. Apparatus used by Tokumoto et al.

The method consists of analyzing the dimensions of a sessile drop resting on a horizontal surface under an atmosphere of purified argon. The shape of the drop depends on an equilibrium between the forces of gravity and surface tension, and can be calculated from the manipulation of the Laplace equation. Bashforth and Adams(6) solved the equation and tabulated their results for values of the parameters X_1, X_2, Z_1, and Z_2, which are shown in Figure 6.

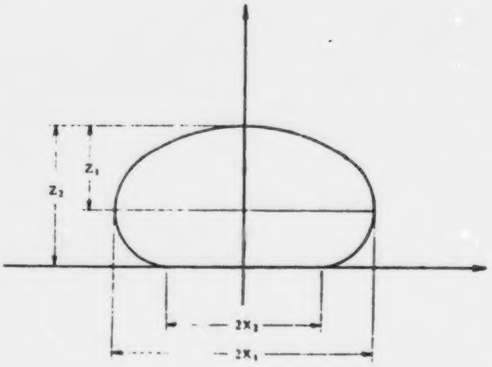


Figure 6. Sketch of meridional section of sessile drop(5).

Surface tension can be determined by measuring X_1 and Z_1, and drop volume can be determined by measuring X_2 and Z_2. Then, density could be determined from the drop mass and drop volume. But X_2 is difficult to measure precisely and the measurement is strongly dependent on human bias. The density data obtained by Tokumoto et al are about 10% lower than other authors' while the surface tension measurements were about 10% higher. The experimental errors were estimated to be 3-4%. The discrepancies of their results were attributed to the purity of the specimens, which were reagent grade.

iv) Maximum Bubble Pressure Technique

Nagamori(7), 1969, used the maximum bubble pressure technique to measure the densities of Cu-S, Fe-S, and Ni-S systems over a wide range of temperatures and compositions. His apparatus is shown in Figure 7.

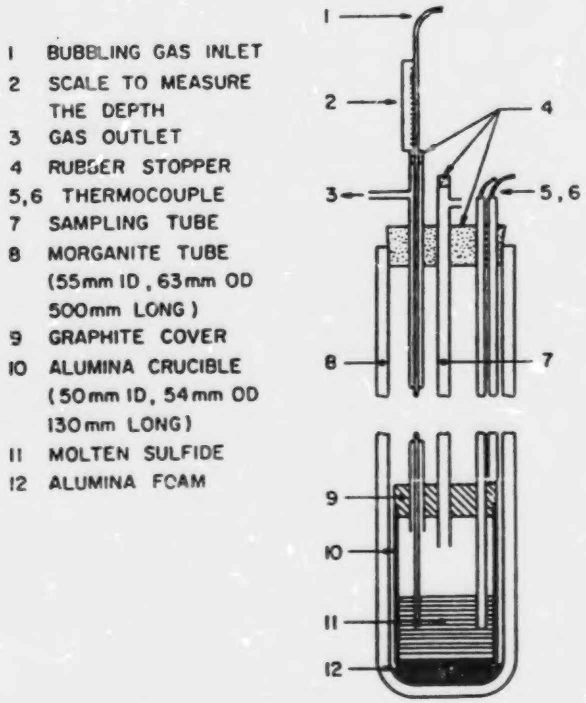

1 BUBBLING GAS INLET
2 SCALE TO MEASURE THE DEPTH
3 GAS OUTLET
4 RUBBER STOPPER
5,6 THERMOCOUPLE
7 SAMPLING TUBE
8 MORGANITE TUBE (55mm ID, 63mm OD 500mm LONG)
9 GRAPHITE COVER
10 ALUMINA CRUCIBLE (50mm ID, 54mm OD 130mm LONG)
11 MOLTEN SULFIDE
12 ALUMINA FOAM
1
2
4
3
5,6
8
7
9
10
11
12

Figure 7. Apparatus used by Nagamori.

A silica tube was immersed to a known depth into the molten sulfides contained in an alumina crucible. By means of a manometer containing dibutyl phthalate, the pressure required to just force a gas bubble through the tube was measured. To minimize the variation of melt composition during a density measurement, the apparatus was constructed to allow either argon, hydrogen, hydrogen sulfide, or mixtures of these gases to be used as the bubbling gas.

In order to obtain accurate and precise data, many compensating factors have to be taken into account. These include the increase in melt level as the capillary is immersed into the melt, the volume of gas in the capillary, and the volume of the gas bubble. Another major concern is the corrosion of the silica capillary tube, since variations of the opening may cause an increase in the apparent density of the matte specimen. The results obtained by Nagamori are reasonable; the error is estimated at 0.3%.

This method seems to be preferred by many scientists in the Soviet Union. Barmin et al(8,9), 1969, 1970, and Dobrovinskii et al(10,11), 1969, 1969, measured the densities along various metal-sulfide binaries at temperatures ranging from 1200 - 1600°C. They claim their expermental error was 3-5%. However, they did not detect any variation in density with temperature. Furthermore, their precision is very low. The bubbling gas they used was helium which has a very high heat capacity. Possibly, the helium was not up to the melt temperature and as a result localized cooling of the matte specimen near the gas bubble may have occurred. This could be one reason why a temperature dependence was not detected. The accuracy of their results must be considered suspect.

Kurochkin et al(12), 1969, measured the density of Cu_2S-FeS mixtures at 1200°C and 1300°C. The bubbling gas they used was purified argon and a temperature dependence was observed. Their experimental error is estimated at 4-6%.

Blagoveshchenskii et al(13), 1976, measured the density of some industrial mattes found in the Soviet Union. Unfortunately, the matte compositions reported were not complete, so that their work can only be considered as qualitative at best.

v) Archimedean Technique

Kaiura and Toguri(14), 1979, used a novel approach to determine the densities of molten mattes. The density of the matte was determined by measuring the buoyant force on an alumina bob of known volume. The apparatus used is shown in Figure 8.

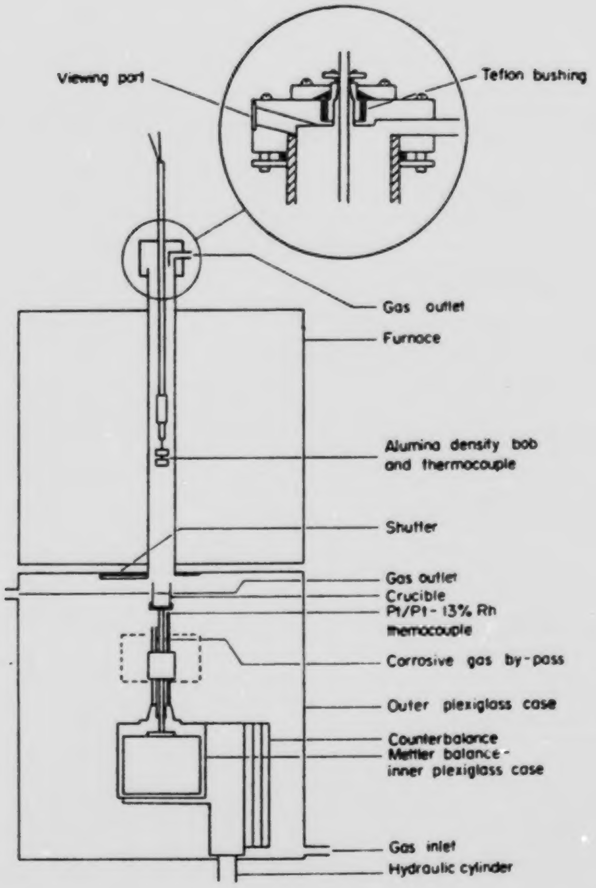

Viewing port
Teflon bushing
Gas outlet
Furnace
Alumina density bob and thermocouple
Shutter
Gas outlet
Crucible
Pt/Pt - 13% Rh thermocouple
Corrosive gas by-pass
Outer plexiglass case
Counterbalance
Mettler balance - inner plexiglass case
Gas inlet
Hydraulic cylinder

Figure 8. Apparatus used by Kaiura and Toguri.

The matte specimen was held in an alumina crucible which was supported by an alumina rod fixed to a balance, so that the weight change of the matte could be continuously measured. The entire assembly was maintained in an argon atmosphere. When the bobs in turn were immersed into the matte, the force on the balance changed.

The weight change caused by immersing the first bob is given by Equation 2, and when both bobs are immersed, the weight change is given by Equation 3. Subtracting gives Equation 4, which can be solved for the density of the matte, since the volume of the bob is known. The surface effect can also be determined by back substitution.

$$W_1/g = (V_1 \cdot D_m) + \text{surface effect} \qquad .....2$$

$$W_2/g = (V_2 \cdot D_m) + \text{surface effect} \qquad .....3$$

$$(W_2 - W_1) / g = (V_2 - V_1) \cdot D_m \qquad .....4$$

where $W_2 - W_1$ is the net weight change
$V_2 - V_1$ is the net volume change
and D_m is the density of the matte

The surface effect is due only to the thin alumina rod connecting the two bobs to each other and to the push-rod. Because it is the same rod with the same diameter, the surface effect associated with it can be eliminated. This method avoids the problem of the surface tension effect that occurs with some of the other techniques.

The compositions studied by Kaiura and Toguri were on the FeS-Cu_2S psuedo binary. Some density data were determined for the Fe-S-O system. The temperature range used was 1200 - 1350°C. The estimated error of their results is 2.2%.

vi) Analyses of Techniques

Only five methods have been used to date to measure the densities of molten mattes. The least accurate of these methods appears to be the U-tube technique. The capillary rise technique shows promise if the surface of the matte is recorded on x-ray film, as demonstrated by Travnichek and Chernomurov. The sessile drop method has as its main problem the sensitivity to the personal biases of the experimentor. However, the surface tension of the matte specimen can be determined simultaneously with density.

Probably the most reliable of the density data mentioned here are those obtained by Nagamori using the maximum bubble pressure technique. But it is also experimentally the most difficult, if precise and accurate data are desired. The Archimedean technique does not seem to be experimentally difficult and is the most elegant technique described here. Problems of surface tension that occur in other techniques are eliminated. It was believed that the relative experimental error reported by Kaiura and Toguri could be decreased. For these reasons it was decided to select this technique for the determination of the densities of molten mattes.

OUTLINE OF RESEARCH PROGRAM

Densities of molten mattes were measuered using a bottom-weighing Archimedean technique. The compositions of the matte specimens are in the five component system Cu-Ni-Fe-S-O. Because it is difficult to express densities in four dimensions, certain ratios were fixed to eliminate two dimensions.

The four component composition diagram Cu-Ni-Fe-S is shown in Figure 9. By setting the Cu/Ni mass ratio to 1, one dimension is eliminated. The composition diagram can then be represented by a triangle with Cu+Ni, Fe, and S on each of the three apices.

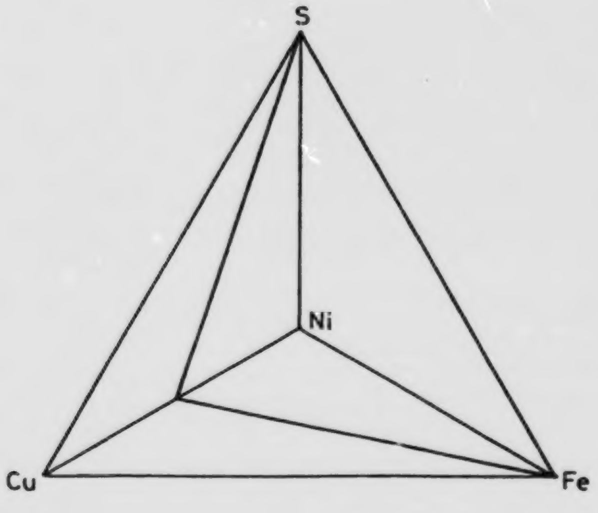


Figure 9. The Cu-Ni-Fe-S composition diagram.

Plotting this triangle against oxygen results in Figure 10. By setting the Fe/O mass ratio to 16, another dimension is eliminated. The composition of the matte specimens can now be represented on a two dimensional triangle with Cu+Ni, Fe+O, and S on each of the three apices.

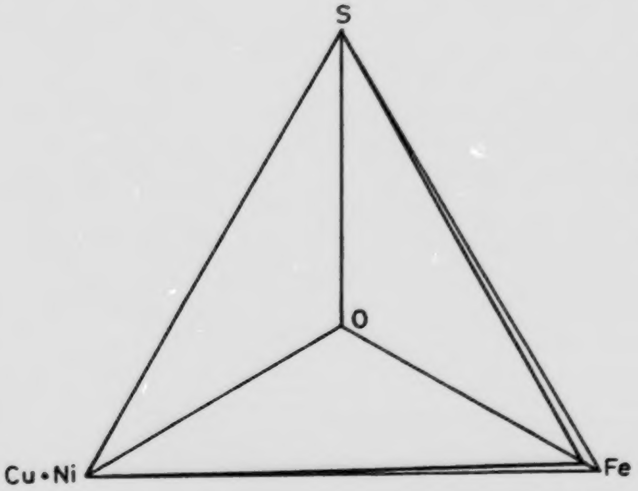


Figure 10. The (Cu+Ni)-Fe-S-O composition diagram.

The choices of the mass ratios used were primarily those of convenience. The densities along the Cu_2S-Ni_3S_2 psuedo-binary have been previously reported(9,11), and are shown in Figure 11.

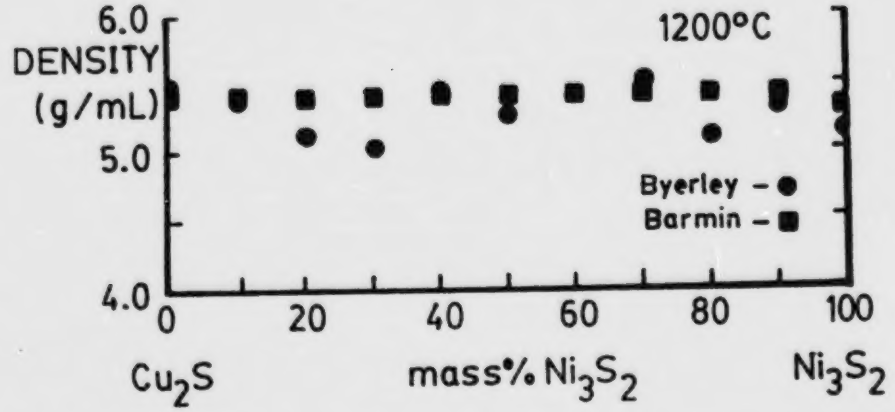


Figure 11. Densities along the Cu_2S-Ni_3S_2 psuedo-binary.

The density does not change significantly with minor deviations from the half and half mixture of the sulfides. The sulfur content of the nickel sulfide is greater than that of the copper sulfide. If the sulfur content of the nickel sulfide is lowered to that of the copper sulfide, it is believed that the density value would again not change significantly from the half and half mixture of the sulfides. It is therefore assumed that minor fluctuations in the copper/nickel ratio will not have a significant effect on the density of a matte specimen.

The Fe/O mass ratio of 16 was selected for different reasons. Figure 12 shows the typical oxygen solubility in furnace mattes(15). The slope of the line indicates an Fe/O ratio 16 to 1. Figure 13 shows the iron and oxygen contents of the matte specimens, and their proximity to the Fe/O = 16 line.

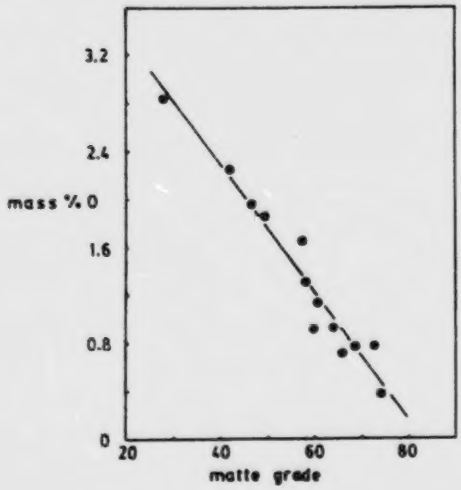


Figure 12. Oxygen solubility in converter mattes(15).

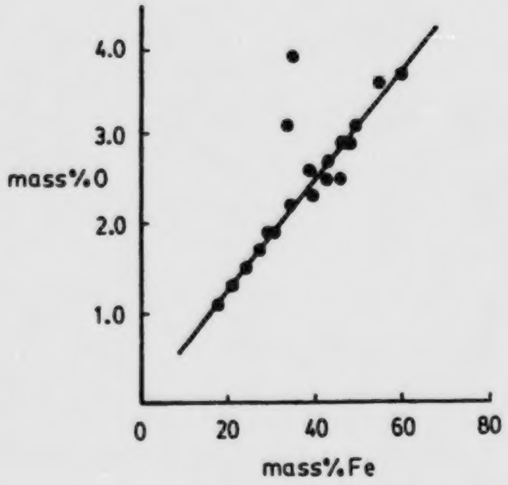


Figure 13. Oxygen content as a function of iron content in converter mattes.

Kaiura and Toguri(14) have measured the densities of iron-sulfur-oxygen mattes. Their results, seen in Figure 14, show a small dependence of oxygen on density in mattes containing low levels of oxygen. If necessary, their data can be used estimate the error in the matte specimen density values resulting from oxygen levels that are greater than those corresponding to the Fe/O mass ratio = 16. Lesser levels of oxygen appear to have little effect on the density.

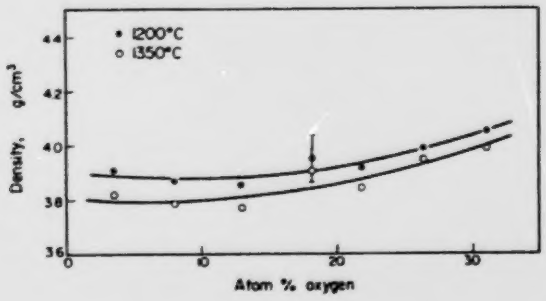


Figure 14. The effect of oxygen on density(14).

The densities of twenty matte specimens were measured in a temperature range of 1100 - 1300°C. Thirteen matte specimens along with their chemical assays were supplied by Falconbridge Ltd. The assays are tabulated in Appendix A. These specimens contained copper, nickel, iron, sulfur, and oxygen along with a few tenths of a percent cobalt. It was assumed that the cobalt content in these mattes had a negligible effect on the density because of the small relative amount. With respect to the sulfur and oxygen in the mattes, it was assumed that cobalt behaved more like iron than either copper or nickel in these mattes. Therefore, the cobalt content was grouped with the iron content. The remaining seven matte specimens had to be synthesized from copper, nickel, iron, sulfur, and iron oxide. The compositions that were investigated are shown in Figure 15.

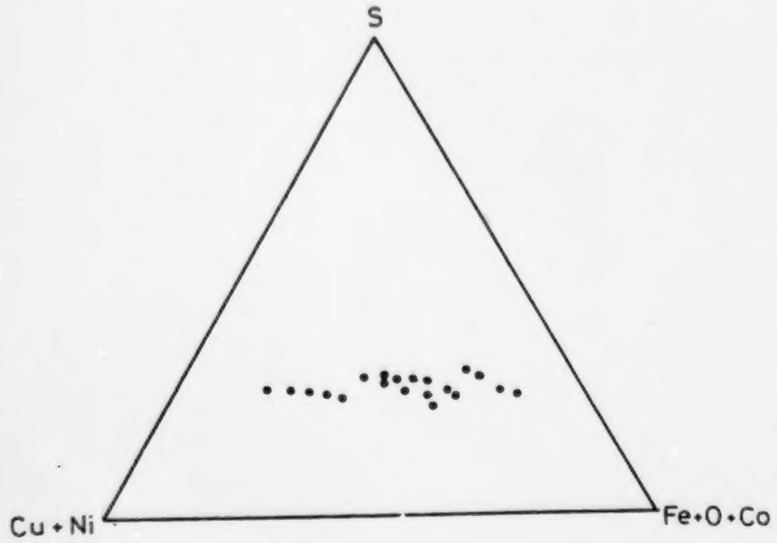


Figure 15. Compositions of matte specimens investigated.

EXPERIMENTAL

i) Apparatus

a) Furnace

An angle iron frame was constructed to hold a Kanthal Super resistance furnace in which the density measurements were to be made. Below the furnace, a drive assembly was constructed to raise the matte specimen into the furnace hot zone. Above the furnace, another drive assembly was constructed to lower the alumina bobs into the molten matte specimen in the furnace.

The furnace was constructed roughly according to a design of a vertical tube furnace as per drawings Y2-3746 in a Kanthal Super furnace design manual(16). The dimensions of the furnace were 62 cm by 62 cm by 82 cm high, while the inner radiation cavity dimensions were 12 cm by 12 cm by 42 cm. Firebricks G30, G26, and G23, obtained from the A.P. Green Fire Brick Co., were used to brick the furnace. Transite, an asbestos board, was used as the furnace shell. The heating elements specified by the designers were not available, so minor modifications in furnace design had to be made. Four Kanthal Super heating elements were used. Their dimensions were Le=400, Lu=250, a=40, and diameters 6 and 12 mm. Each of these elements was rated at 2070 watts at 14.8 volts. The elements were placed 10 to 15 mm from the reaction tube and surrounding it. The reaction tube was made of MV30 material and was supplied by McDanel Refractories. MV30 is a fine grained mixture of 85% mullite and 15% glass. It was selected over both pure alumina and mullite compositions because of its superior thermal shock resistance. The dimensions of the reaction tube were 57 mm I.D., 63 mm O.D., and 122 cm long. The furnace is illustrated in Figure 16.

The elements were first connected to the power circuit by means of mechanically bolted copper lugs. It was not certain that these types of connections gave the necessary contact of the elements with the copper lugs in order to carry the large current required. The aluminized ends of the elements were not to exceed a temperature of 200°C because of potential damage that might occur to the aluminized contacts. Therefore, soft solder thermal breakers were installed into the power circuit near the element contacts. As the temperature of the furnace reached 1000°C, these soft solder breakers failed, indicating that localized overheating was occurring at the copper/element contact points. It was later determined that the best contact material was a tin coated braided copper wire, which had a larger contact area with the aluminized ends of the elements.

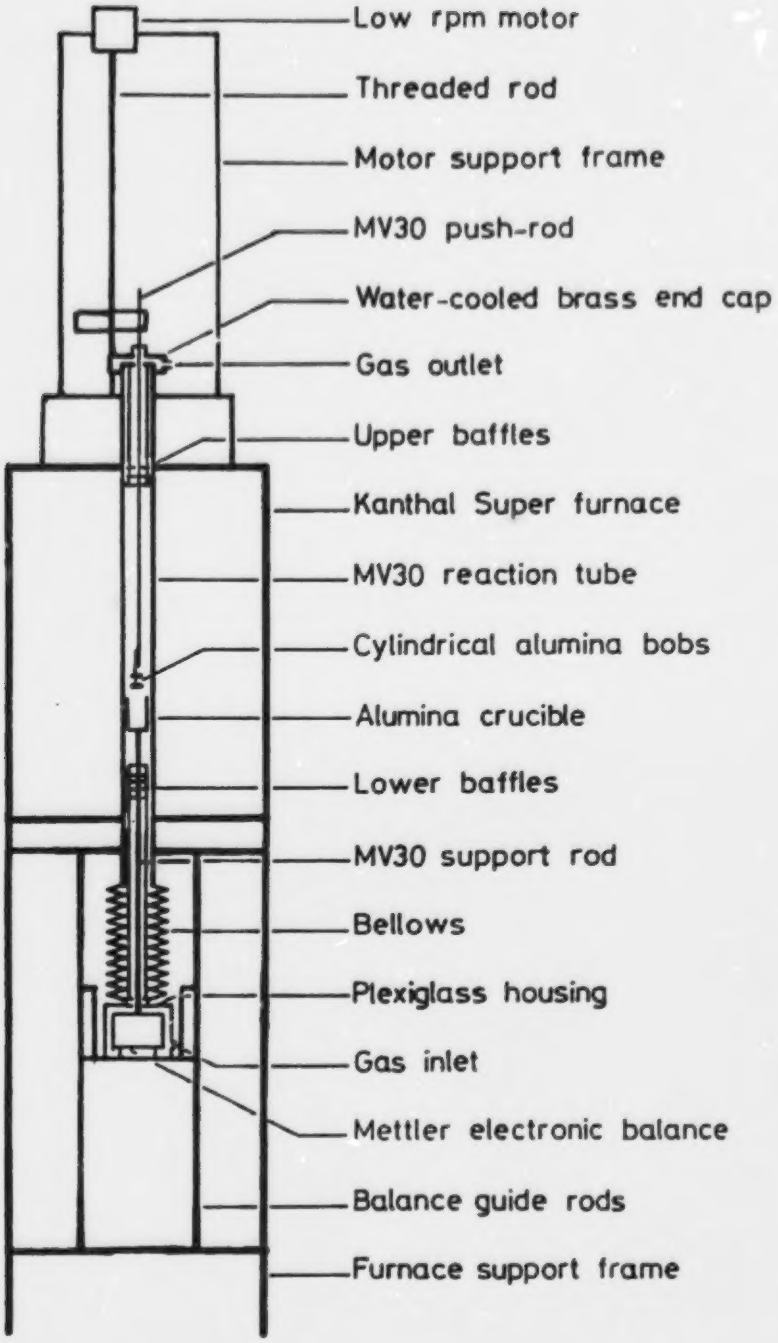

Low rpm motor
Threaded rod
Motor support frame
MV30 push-rod
Water-cooled brass end cap
Gas outlet
Upper baffles
Kanthal Super furnace
MV30 reaction tube
Cylindrical alumina bobs
Alumina crucible
Lower baffles
MV30 support rod
Bellows
Plexiglass housing
Gas inlet
Mettler electronic balance
Balance guide rods
Furnace support frame

Figure 16. Apparatus.

The temperature of the furnace was indicated by a platinum / platinum-13%rhodium thermocouple placed in the inner radiation cavity of the furnace. The hot junction was in contact with the outer wall of the reaction tube in the center of the furnace hot zone. The other end of the thermocouple was connected to an Omega model 650 Type R electronic thermometer with automatic cold junction compensation.

b) Power Considerations

Power to the furnace was supplied from a 208 V, 30 A electrical outlet via two transformers. The first transformer was variable, and stepped down the voltage to 75-150 volts, depending on the power requirements of the furnace. The second transformer was fixed at a ratio of 5:2 and was used to generate the high current. The operating voltage of the four elements connected in series varied from 30 to 60 volts, depending on the furnace temperature required. The operating current remained relatively constant at 75 A at all temperatures from 1000 - 1400°C. This indicated that the mode of heat loss from the furnace was primarily conduction and convection. Because the resistance of the $MoSi_2$ Kanthal Super elements increases linearly with increasing temperature, the power to the furnace varied linearly with voltage and furnace temperature. Therefore, it was not necessary to use an automated temperature controlling device, since the temperature was easily controlled with voltage via the variable transformer. The furnace power circuit is shown in Figure 17.

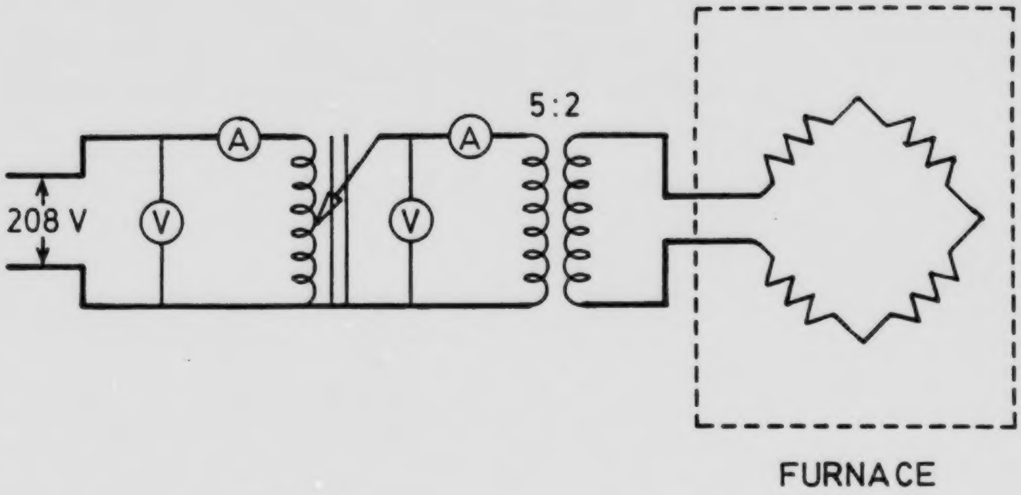


Figure 17. Circuit diagram for furnace.

c) Lower Drive Assembly

The balance used was a Mettler PL1200 top loading electronic balance. It had a readability of 0.01 grams, with a maximum capacity of 1200 grams, and a rated precision of 0.005 g. The balance was chosen because it was equipped with a vertical stability indicator which could indicate if the crucible was in contact with the inner wall of the reaction tube while in the hot zone of the furnace. Also, a new weight reading was provided every 0.6 seconds. This response time was found to be more than adequate for that required during the measurements. An external electronic tare was also connected to the balance so that it could be zeroed remotely. The balance weighing assembly was modified to hold an 8.5 mm diameter, 56 cm high MV30 support rod with a fireclay pedestal on which a crucible containing the matte specimen was held. A splash shield was mounted on the balance in order to prevent any molten matte from coming in contact with the balance should the crucible fail in the furnace.

The balance was enclosed in a 12 mm thick plexiglass case which also served as a ballast for the incoming argon gas. The top of the plexiglass case was fitted with a water cooled brass end cap which would come in contact with the bottom of the reaction tube when the balance was raised to the 'up' position. The brass end cap also supported a series of seven Inconel 900 discs supported by three 4 mm diameter, 50 cm high Inconel rods which served as radiation baffles. A 12 mm diameter hole was drilled through the center of these baffles to allow sufficient clearance for the support rod. Also, one end of removable plastic bellows was fastened to the end cap, while the other end of the bellows could be connected to the bottom of the reaction tube via a water cooled brass ring and a butyl rubber O-ring. This connection was made when a matte specimen was placed on the support platform with the balance in the down position, so that the atmosphere around the matte could be purged while the matte remained cool. The balance could be raised or lowered on guide rods by means of a motorized threaded rod. A counterweight was used to minimize the moment on the threaded rod.

The crucibles were made of 99.98% dense, fine grained alumina and were manufactured by Home Technics Ltd. in Peterborough. They were 78 mm high, 45 mm in diameter, and had a wall thickness of 3 mm. Alumina was selected because of its high chemical inertness. Unfortunately, alumina has rather poor thermal shock resistance properties, so that the crucible had to be raised relatively slowly into the hot zone of the furnace in order to prevent failure.

d) Upper Drive Assembly

The upper drive assembly consists of a threaded rod driven by a reversible variable speed motor. An MV30 ceramic closed end tube, 8.5 mm diameter and 92 cm long, was connected to the threaded rod by means of a cross bar. This enabled it to be moved into the furnace along guide rods in a precise and definite fashion. The top of the reaction tube was fitted with a water cooled brass end cap. The end cap was secured to the reaction tube by means of O-ring, gas tight seals. The end cap had a centrally located opening fitted with an O-ring seal through which the ceramic push rod passed. To minimize friction restrictions, the O-ring was lubricated with a silicone based lubricant to alleviate any binding or sticking of the push rod to the O-ring.

The upper radiation baffles consisted of a series of five Inconel 900 discs with their centers cut out. They were suspended from the end cap via three Inconel rods, 4 mm in diameter and 40 cm long. The push rod, with alumina bobs attached, was eased through the centers of the radiation baffles and into the hot zone of the furnace. This was facilitated with the use of a pyrex window located on the top of the end cap.

e) Alumina Bobs

The alumina bobs were made of 99.98% fine grained dense alumina, and were also manufactured by Home Technics Ltd. The bob assembly consisted of two alumina cylinders, each 10.7 mm in diameter and 17.9 mm long, and a thin alumina rod, 1.8 mm in diameter and 100 mm long. A 2.0 mm diameter hole was electrosonically drilled through the center of one cylinder, and partially through the center of the other cylinder. The rod was passed through the hole in one cylinder and into the other cylinder. The cylinders were adjusted with one cylinder at the bottom of the thin alumina rod, the other about 10 mm above it. This assembly was cemented in place with alumina cement and fired at $1600^{o}C$ for several hours. After firing, a small amount of Aremco Ceramabond #503 alumina cement was placed on each joint between the rod and cylinders. This ensured that the molten matte would not seep into the joint during the experiments. After curing the cement, the bobs were ready to be attached to the push rod.

The bobs were fastened to the ceramic push rod via platinum and nichrome wires and cemented with Aremco Ceramabond #503 alumina cement. This ensured the bobs would not detatch from the MV30 push rod. A platinum / platinum-13%rhodium thermocouple was placed inside the push rod and was used to monitor the temperature of the melt when the bobs were immersed into the matte specimen. The bob and crucible arrangement is shown in Figure 18.

f) Gas Train

The gas used during the experiments was gettered argon. The gas train consisted of a column of drierite to remove any moisture content in the argon. A rotameter was used to control the flowrate. The gas then passed through a getter furnace filled with copper turnings. The temperature of the furnace was monitored with a chromel/alumel thermocouple and

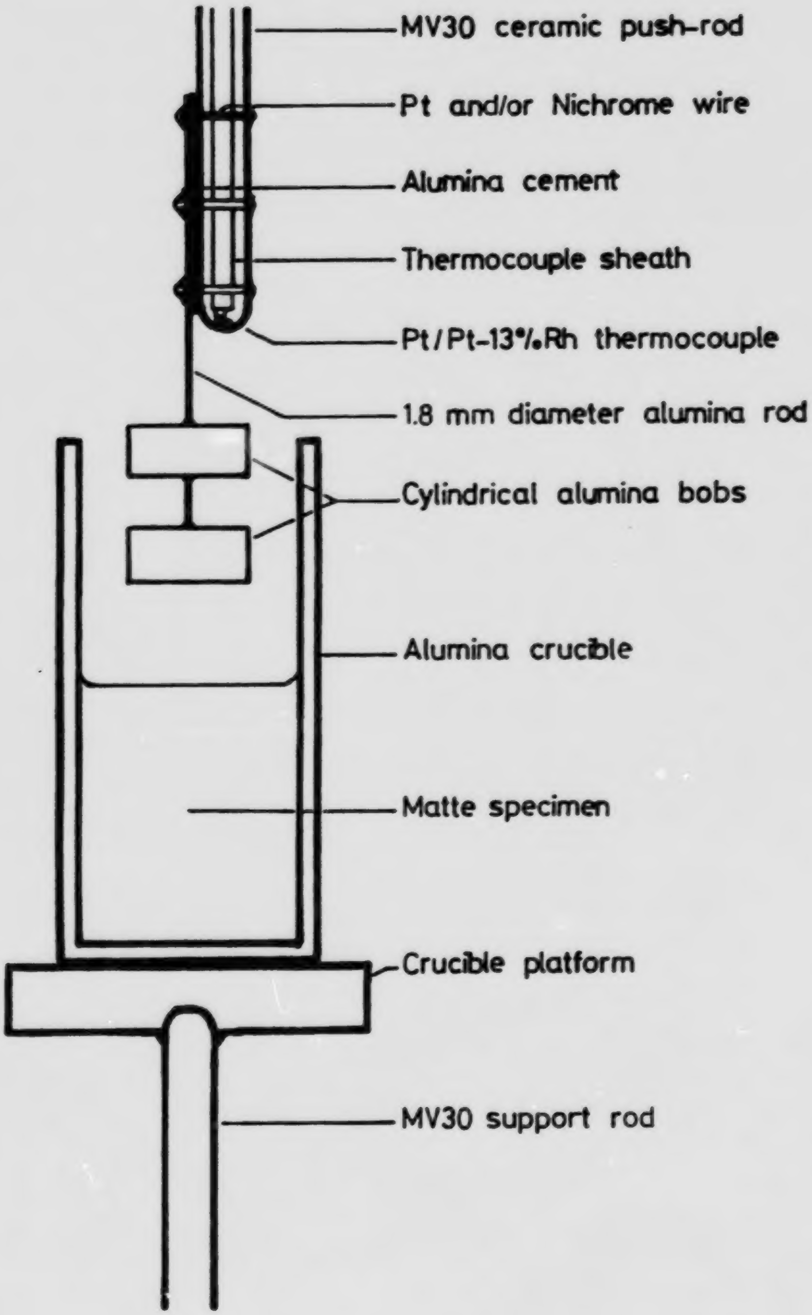

MV30 ceramic push-rod
Pt and/or Nichrome wire
Alumina cement
Thermocouple sheath
Pt/Pt-13%Rh thermocouple
1.8 mm diameter alumina rod
Cylindrical alumina bobs
Alumina crucible
Matte specimen
Crucible platform
MV30 support rod

Figure 18. Bob and crucible arrangement.

controlled with a small variable transformer. A temperature of 450°C ensured that the argon atmosphere would be essentially oxygen free, that is, the residual oxygen level would be so low that it could not add significantly to the oxygen content of the samples. The gas then passed through a bubbler containing dibutyl phthalate and into the plexiglass case which housed the electronic balance. It was decided to pass the gas through the balance assembly first to prevent any corrosive sulfur gases from reaching the balance, as this could cause damage to the internal circuits of the balance. The gas then passed through the reaction tube and out through the gas exit port in the top brass end cap. Finally, the gas passed through a small bubbler filled with dibutyl phthalate and into the atmosphere of the laboratory. The bubbler prevented any oxygen from back diffusing into the reaction tube. A schematic of the gas train is shown in Figure 19.

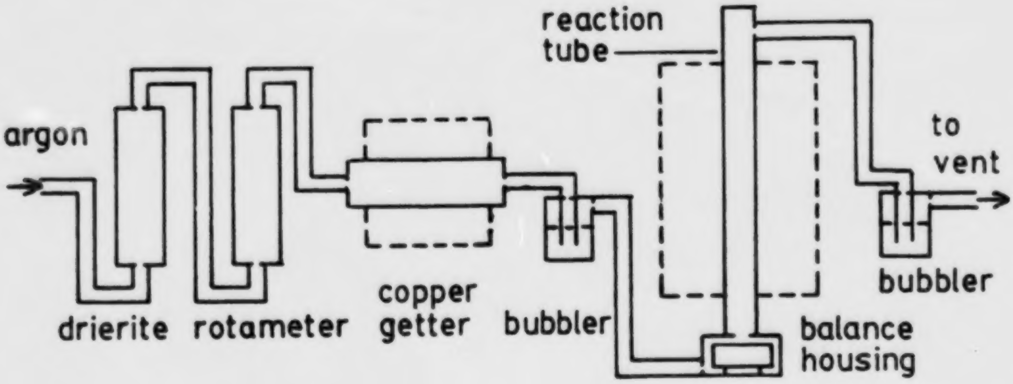


Figure 19. Gas Train.

ii) Specimen Preparation

Thirteen of the twenty matte specimens were supplied by Falconbridge Ltd. These specimens were made by adding small amounts of copper, nickel, and sulfur to several electric furnace mattes and fusing the mixtures at 1500°C in an induction furnace under an air atmosphere. This method produced low grade matte specimens with oxygen contents typical of those found in furnace mattes. Because the starting material was an electric furnace matte, the specimens also contained a few tenths of a percent cobalt. About 220 grams of each matte specimen were provided along with the chemical assays, which are tabulated in Appendix A.

The remaining seven matte specimens were synthetically produced in the laboratory. The starting materials for these mattes were commercially pure electrical grade copper, electrolytic nickel, electrolytic Armco iron, technical grade magnetite, and sublimed flowers of sulfur. The nickel and iron were supplied by Falconbridge Ltd. The sulfur was obtained from BDH Chemicals. The matte specimens were made individually by combining synthetically prepared copper, nickel, and iron sulfides, with magnetite. The target compositions, as well as the amounts of starting materials required for each of the matte specimens are tabulated in Appendix B. An outline of the procedure for preparing each matte specimen is shown in Figure 20.

STARTING MATERIALS

Cu	Ni	Fe	S	Fe_3O_4
machined to 0.02 gram chips on a milling machine			purified under vacuum while molten	dried under Ar at 500°C
deoxidized with hydrogen at 450°C			solidified	

combined with sulfur in ratios:

2Cu:1S	3Ni:2S	Fe and remaining S
	OR	
Cu and remaining S	3Ni:2S	Fe:S

sealed in pyrex tubes under vacuum
and reacted at 550°C to form sulfides

separated from pyrex, crushed,
combined with Fe_3O_4 and mixed

placed into an alumina crucible

Figure 20. Outline of the specimen preparation procedure.

The first step in the procedure was to prepare the starting materials. The purity of the metals was sufficient for the determination of matte densities. Copper, nickel, and iron were machined into 0.02 gram chips on a milling machine. The size of the metal chips turned out to be an important parameter, as will be discussed later. After milling, the copper, nickel, and iron chips were deoxidized with hydrogen at 450°C because during milling in air, the metal chips may have reached a high enough temperature to partially oxidize. This was especially true for the iron chips. After deoxidation, the metal chips were combined with sulfur.

The sulfur that was used had a purity of about 98%, with most of the impurities being carbonaceous matter. The sulfur was purified by melting it in a pyrex tube under vacuum to remove the volatile organic materials and adsorbed water. The sulfur was kept molten and under vacuum until it appeared transparent. Solidification was allowed to occur in the pyrex tube. The tube was then broken and separated from the sulfur. This resulted in large pieces of relatively pure sulfur that were much easier to handle than the fine sulfur flowers. The procedure left the sulfur ready to be combined with the metal chips.

The purity of the magnetite was unknown, but was believed to be 85-95%. Magnetite was used to set the oxygen level in the matte specimens, so only small amounts of magnetite were required. It was believed that the magnetite could be made sufficiently pure for this purpose. The main impurity in the magnetite was adsorbed water. Therefore, purifying was done by heating the magnetite to 500°C under an argon atmosphere. A rough mass balance calculation indicated that the water content in the initial magnetite was about 5%.

The next step was to produce the metal sulfides. Copper for one matte specimen was placed into a pyrex tube with enough sulfur to produce stoichiometric Cu_2S. A required amount of nickel and sulfur to produce stoichiometric Ni_3S_2 was placed into a second pyrex tube. Some of the required iron needed to make a matte specimen would be added as magnetite. The remaining required iron was placed into a third pyrex tube with the remaining required sulfur only if the overall composition in the tube did not contain more sulfur than was needed to form stoichiometric FeS. Otherwise, only the amount of sulfur needed to make stoichiometric FeS was used. The remaining required sulfur was added to the tube containing copper and sulfur. The sulfur was distributed in this way because of the kinetics involved in synthesizing the different metal sulfides. The reaction rate of copper and sulfur is greater than that of nickel and sulfur, and much greater than that of iron and sulfur. These differences result primarily from differences in the sulfide crystal structures.

The three pyrex tubes containing the metal-sulfur mixtures were sealed under vacuum. Each tube was then placed into a small furnace at 550°C in such a way as to have one end of the tube outside the furnace at room temperature. Sulfur exerts a pressure of one atmosphere at 445°C. But because it is allowed to condense at the cold end of the tube, the pressure can be kept relatively low by controlling the amount of gaseous sulfur at the hot end of the tube. By keeping one end of the tube at a high temperature (550°C), the poor kinetics of the reaction at low temperatures can be overcome. But by keeping the other end of the tube at room temperature, the amount of sulfur at the reaction site, and hence, the reaction rate, can be easily controlled.

The metal-sulfur reaction is extremely exothermic and autogeneous once started. If the metal chips are too small, the temperature at the reaction site can increase rapidly because of the high surface to volume ratio of the chips. If the metal chips are too large, the reaction rate decreases, as diffusion must occur through a relatively thick sulfide outer shell. It was found that sulfides could be made within a few hours at 550°C in a controlled manner if the size of the metal chips was small and had masses in the order of 0.02 grams. The whole procedure of making sulfides is a compromise between control of the reaction and the reaction rate. Acceptable control of the reaction was achieved at 550°C, and, at this temperature, the reaction rate was fairly rapid.

After all of the sulfur had reacted with the metal, the tube was cooled slowly to prevent the pyrex from cracking due to thermal shock. Also, this prevented the matte from adhering to the inner wall of the tube. The relatively greater thermal contraction of the sulfides compared to the pyrex combined with the adhesion of the sulfides to the glass can cause failure due to cracking during cooling.

After the sulfides had cooled, they were separated from the pyrex tube and weighed to determine the amount of material lost. In all cases, over 99.9% of the material was recovered. The three sulfides that pertained to one matte specimen were combined, crushed, mixed with the appropriate amount of magnetite, and placed into a crucible. The volume of the crucible was sufficient to hold the 250 g of the sulfide and magnetite mixture. Final matte synthesis would occur at the same time the densities of the matte specimens were to be measured.

iii) Technique

a) Derivation of Equations

Archimedes' principle states that the density of an object can be determined by measuring the net gravitational force on the object while it is immersed in a fluid of known density. This value is then compared to one obtained with the object in a vacuum. Archimedes discovered this principle by weighing a gold crown in water, and then in air. He determined that the crown was actually made of a gold alloy, with a density less than that of pure gold. (The metallurgist who made the crown has not been heard from since.)

The net gravitational force on an object immersed in a fluid, or the weight of the object, is determined from its mass subtracting the mass of the fluid the object displaces, and multiplying by 'g', the acceleration due to gravity. If the fluid is air, the displaced mass is usually small and is often ignored. The density of the object is then determined using Equation 6.

$$M = W_f/g + V \cdot D_f$$

And:

$$M = W_a/g + V \cdot D_a$$

where: M = mass of an object

V = volume of the object

W_a = weight of the object in air

W_f = weight of the object in a fluid

D_a = density of air

D_f = density of the fluid

Therefore:

$$W_f/g + V \cdot D_f = W_a/g + V \cdot D_a$$

$$V = (W_a/g - W_f/g) \;/\; (D_f - D_a) \qquad \ldots\ldots.5$$

Also:

$$V = (M - W_f/g) \;/\; D_f = (M - W_a/g) \;/\; D_a$$

$$(M - W_f/g) \;/\; D_f = (M - W_a/g) \;/\; D_a$$

$$M \cdot (D_a - D_f) = (D_a \cdot W_f/g) - (D_f \cdot W_a/g)$$

$$M = [(D_a \cdot W_f/g) - (D_f \cdot W_a/g)] \;/\; (D_a - D_f)$$

$$D = M \;/\; V$$

$$D = [(D_a \cdot W_f/g) - (D_f \cdot W_a/g)] \;/\; (W_f/g - W_a/g) \qquad \ldots..6$$

If the volume of an object is known, the density of a fluid can be determined by using Equation 5 above, if the object is denser than the fluid. Otherwise, the object will float like a bob. In that case, the fluid must be weighed in a crucible, for example, with the bob forcibly immersed into the fluid. The density of the fluid can then be determined using Equations 7a and 7b.

mass of crucible including sample (in air) $= W_c/g + (V_c \cdot D_a)$

mass of crucible with bob immersed $= W_{cb}/g + W_b/g + [(V_c + V_b) \cdot D_a]$

mass of bob (immersed in fluid) $= W_b/g + (V_b \cdot D_f)$

where: W_c = weight of crucible and sample (in air)

W_{cb} = weight of crucible and sample with bob immersed

W_b = weight of bob immersed in fluid

V_c = volume of crucible and sample

V_b = volume of bob

Therefore:

$$W_c/g + V_c \cdot D_a + W_b/g + V_b \cdot D_f = W_{cb}/g + W_b/g + (V_c+V_b) \cdot D_a$$

$$V_c \cdot D_a + V_b \cdot D_f - (V_c+V_b) \cdot D_a = W_b/g - W_b/g + W_{cb}/g - W_c/g$$

$$V_b \cdot (D_f - D_a) = W_{cb}/g - W_c/g \qquad ....7a$$

$$D_f = [(W_{cb}/g - W_c/g) / V_b] + D_a \qquad ....7b$$

Equations 7a and 7b were utilized in the calculation of the densities of the matte specimens.

The measured value 'W_{cb}' in Equation 7b includes a term associated with a surface tension effect, which leads to an erroneous value of the fluid density. The bob is connected to a thin rod which penetrates the fluid surface. If the interfacial tension between the rod and fluid is identical to the surface tension, the magnitude of the surface effect would be zero. Otherwise, this surface effect would have a positive or negative value, depending on the wetting characteristics of the rod with the fluid. However, this effect can be eliminated by measuring two values of 'W_{cb}' with two bobs connected by a vertical rod of the same material and diameter as the rod supporting the upper bob, as shown in Figure 18. By subtracting two equations, one applying when only the lower bob is immersed and the other when both bobs are immersed, a net 'W_{cb}' value can be obtained from the volume of the upper bob with a net zero surface effect contribution. The density of the fluid can then be obtained free from surface effect contributions. This is illustrated in the derivation of Equations 8a and 8b from Equation 7a.

With only one bob immersed:

$$W_{cb}(1)/g - W_c/g = [V_b(1) \cdot (D_f - D_a)] + \text{surface effect at rod connecting the two bobs}$$

With both bobs immersed:

$$W_{cb}(2)/g - W_c/g = [V_b(2) \cdot (D_f - D_a)] + \text{surface effect at rod supporting the upper bob}$$

where: $W_{cb}(1)$ = weight of crucible with lower bob immersed

$W_{cb}(2)$ = weight of crucible with upper bob immersed

$V_b(1)$ = volume of lower bob

$V_b(2)$ = volume of both bobs

Subtracting:

$$W_{cb}(2)/g - W_{cb}(1)/g = [V_b(2) - V_b(1)] \cdot (D_f - D_a) \quad ..8a$$

$$D_f = [(W_{cb}(2)/g - W_{cb}(1)/g) / (V_b(2) - V_b(1))] + D_a \quad ..8b$$

As evident in Equation 8b, only the volume of the upper bob, i.e., $[V_b(2) - V_b(1)]$, had to be determined in order to calculate the density of the matte specimen. The volume of the bob was determined using mercury as the fluid in Equation 8b. Mercury was selected because its density is high and well established in the literature$^{(17)}$. Because of its high density, the magnitude of '$W_{cb} - W_c$' is large, which increases the precision in calculating the volume of the second bob. Also, the density of air becomes insignificant when compared to the density of mercury, so the value of 'D_a' in Equation 8b can be set to zero.

From Equation 8a above:

$$W_{cb}(2)/g - W_{cb}(1)/g = [V_b(2) - V_b(1)] \cdot [D_f - D_a]$$

Let:

D_f = density of mercury
= D_{mer}

D_a = density of air
= 0

$W_{cb}(2) = W_4$
= weight of crucible with both bobs immersed

$W_{cb}(1) = W_3$
= weight of crucible with lower bob immersed

$V_b(2) - V_b(1)$ = volume of upper bob
= V_{bu}

Therefore:

$$W_4/g - W_3/g = V_{bu} \cdot D_{mer}$$

$$V_{bu} = (W_4 - W_3)/g / D_{mer} \qquad ....9$$

After determining the volume of the upper bob at room temperature, the volume of the bob at high temperatures must be calculated. The bobs were made of high purity dense alumina with a thermal expansion coefficient of 8.5×10^{-6} per degree, as stated by the manufacturer. The bobs can be approximated to spheres in shape, so that the volume of the bobs at high temperatures can be calculated by Equation 10.

Let the volume of the upper bob at room temperature = V_o

$$V_{bu} = V_o \cdot [1 + ((8.5 \times 10^{-6}) \cdot (t - rt))]^3 \quad .....10$$

where:
t = bob temperature in degrees C
rt = room temperature in degrees C

b) Procedure

With the volume of the second bob calculated, the densities of the matte specimens can now be determined. The bobs, attached to the upper MV30 push rod, are placed into the furnace through the top end cap. The push rod is connected to the upper drive assembly so as to lower the bobs into the furnace in a slow and precise manner. With the bobs lowered, the opening through which the push rod passes is sealed by means of an O-ring. The rod is lubricated with a silicone based lubricant to prevent it from sticking to the O-ring while maintaining a gas tight seal.

the inner wall of the reaction tube, and the bobs could be immersed into the matte specimen without coming into contact with the inner wall of the crucible. This also allows the alumina bobs to equilibrate thermally with the surroundings. The bobs are then totally immersed into the matte specimen and withdrawn. This mixing action ensures that the matte is homogeneous. This also wets the bobs with the matte and deposits a thin film of molten matte onto the surface of the bobs. Also, a small drop of matte is left hanging from the bottom of the first bob. This procedure left the bobs and matte specimen ready for obtaining the data required for the density calculations.

With the balance zeroed, the bobs were immersed into the matte in 1.4 mm increments. After each increment, the weight change indicated by the balance was recorded. When both bobs were fully immersed, the temperature indicated by the thermocouple in the push rod was recorded. The position of the thermocouple at that time was a few millimeters above the surface of the matte. Therefore, the temperature recorded was assumed to be that of the specimen. The bobs were then withdrawn from the matte and the overall weight change recorded. This weight change was assumed to be the result of sulfur evolution from the matte specimen. Usually, this weight change was zero. However, when the weight change was large (in the order of 0.05 g), the data were adjusted assuming uniform sulfur evolution during the measurements. The procedure was repeated two or three times at the same temperature.

The measurements were first made at a temperature of about 1300°C. The temperature was then lowered some 50 degrees and after thermal equilibration, the above procedure was repeated. When the bobs were immersed into the matte and then withdrawn, the size of the matte droplet on the bottom of the first bob had increased because of the change in surface tension of the matte at the lower temperature. The extent of sulfur evolution at the lower temperatures was considerably less than at higher temperatures. Overall weight losses never exceeded 0.02 g.

With the completion of the measurements at about 1250°C, the furnace temperature was lowered in about 50 degree decrements with measurements taken at each temperature level. The final measurements were taken at about 1100°C. The matte specimen was then slowly lowered out of the furnace and replaced with another matte specimen. The entire procedure was then repeated for all matte specimens. Representative matte samples were then obtained from each specimen for chemical analyses.

RESULTS

The results of the chemical analyses of the twenty matte specimens, as received from Falconbridge Ltd., are tabulated in Appendix C. The assays were normalized and grouped, as previously mentioned, and are listed in Tables 1 and 2. The ratios of the grouped elements are also shown.

Table 1. Normalized compositions and ratios of the first thirteen matte specimens.

SPECIMEN	COMPOSITIONS (mass %)			RATIOS	
NUMBER	Cu+Ni	Fe+O(+Co)	S	Cu/Ni	Fe(+Co)/O
B3	35.9	35.8	28.3	1.02	18.9
B6	16.6	53.3	30.1	0.99	14.1
B7	20.3	51.9	27.8	0.98	14.4
B12	24.5	49.3	26.2	0.97	20.3
B13	26.6	45.7	27.7	0.98	18.2
B14	29.5	42.4	28.1	0.97	17.6
B16	33.1	38.2	28.7	0.99	17.8
B17	33.0	41.6	25.4	0.96	21.1
B18	35.2	37.3	27.5	0.97	19.1
B19	38.3	33.1	28.6	0.98	20.3
B20	15.7	58.8	25.5	0.94	16.6
B21	23.7	52.1	24.2	0.94	23.4
B22	28.1	46.4	25.5	0.99	21.1

Table 2. Normalized compositions and ratios of the seven synthesized matte specimens.

SPECIMEN	COMPOSITIONS (mass %)			RATIOS	
NUMBER	Cu+Ni	Fe+O	S	Cu/Ni	Fe/O
C16	44.4	30.0	25.6	0.97	23.8
C17	46.8	27.3	25.9	1.01	18.7
C18	50.0	23.7	26.3	1.01	23.3
C19	53.3	20.0	26.7	0.98	32.7
C20	57.0	16.3	26.8	0.88	36.6
C24	29.6	46.8	23.6	1.01	25.9
C25	13.3	60.9	25.8	0.99	27.0

The densities of the matte specimens were evaluated using Equation 11.

$$D_{matte} = [(W_2-W_1)/g] \;/\; V_{bu}$$
$$= [(W_2-W_1)/g] \;/\; [V_o \cdot [1+(LCTE_a \cdot (t-25))]^3]$$
$$= \frac{(W_2 - W_1)}{(W_4 - W_3)} \cdot \frac{D_{mer}}{[1+(LCTE_a \cdot (t-25))]^3} \quad \ldots\ldots 11$$

where:

D_{matte} = the density of the matte specimen

W_2 = the net weight change recorded with both bobs immersed into the matte

W_1 = the net weight change recorded with the lower bob immersed into the matte

W_4-W_3 = the net weight change recorded with the upper bob immersed in mercury during calibration of bob volume

D_{mer} = the density of mercury = 13.546 g/mL

$LCTE_a$ = the linear coefficient of thermal expansion of the alumina bobs = 8.5×10^{-6} / C°

t = the temperature of the matte specimen in C° at the time the measurements were taken

The values of '$(W_4-W_3)/g$', 't', 'W_1/g', 'W_2/g', '$(W_2-W_1)/g$', and 'D_{matte}' for each measurement are listed in Appendix D. Figures 21a and 21b show the density data of the matte specimens as a function of temperature.

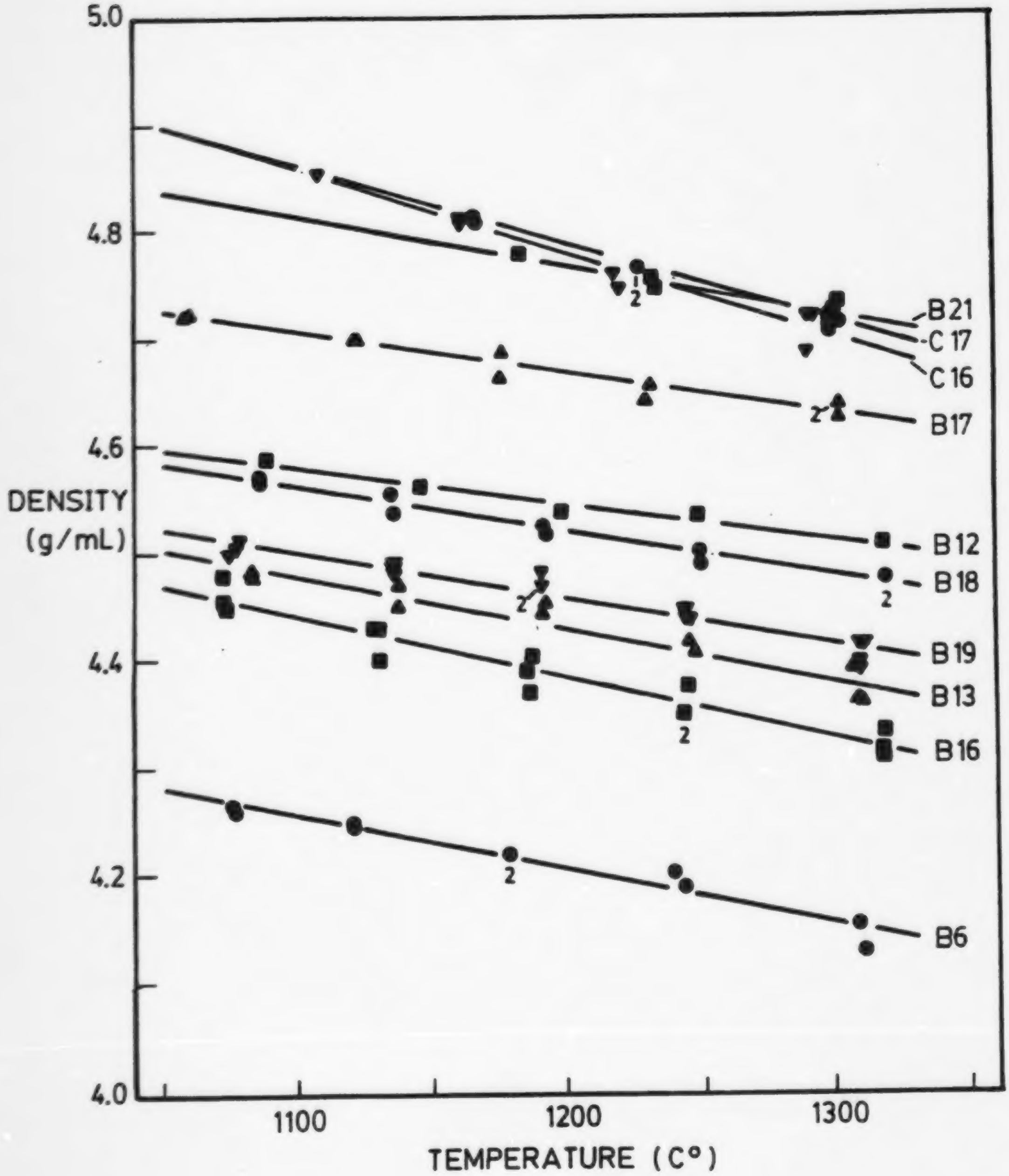


Figure 21a. Density data as a function of temperature.

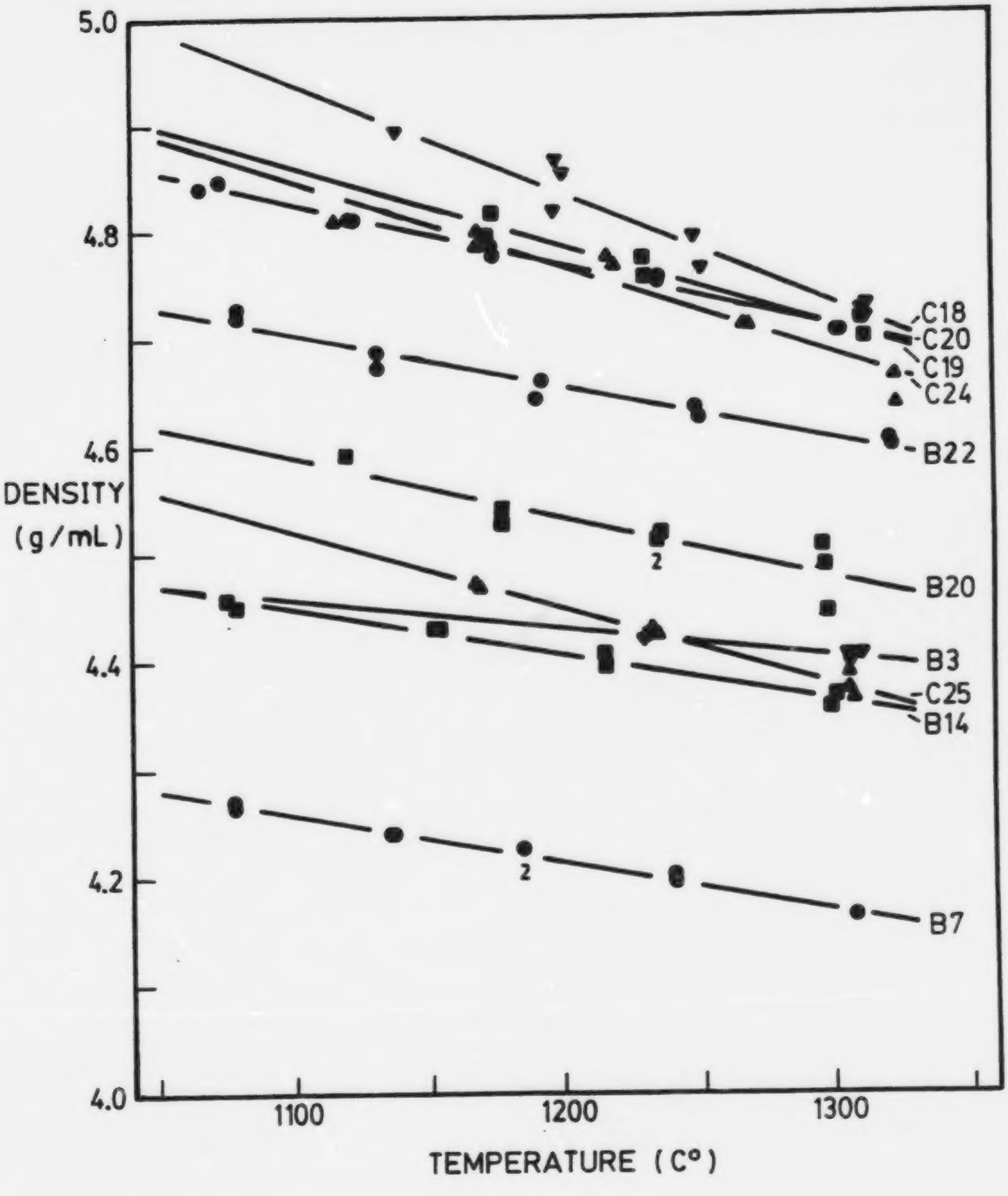


Figure 21b. Density data as a function of temperature.

The densities of the matte specimens at 1100°C, 1200°C, and 1300°C were calculated by linear regression of the raw data in Appendix D. The densities, standard errors of estimate, the correlation coefficient 'R', and the temperature coefficient 'Alpha' of each matte specimen are listed below in Table 3.

Table 3. Densities of the matte specimens.

SPECIMEN NUMBER	DENSITY			STD ERROR OF ESTIMATE	R	ALPHA x1000
	1100°C	1200°C	1300°C			
B3	4.459	4.432	4.404	0.004	0.954	0.275
B6	4.258	4.207	4.155	0.010	0.979	0.512
B7	4.260	4.216	4.172	0.003	0.996	0.444
B12	4.580	4.546	4.512	0.005	0.988	0.340
B13	4.477	4.428	4.379	0.011	0.943	0.491
B14	4.450	4.407	4.364	0.007	0.987	0.426
B16	4.441	4.384	4.327	0.014	0.968	0.574
B17	4.706	4.668	4.629	0.008	0.977	0.385
B18	4.562	4.521	4.479	0.007	0.984	0.418
B19	4.503	4.459	4.414	0.010	0.970	0.444
B20	4.587	4.532	4.477	0.018	0.888	0.547
B21	4.814	4.768	4.723	0.008	0.948	0.454
B22	4.705	4.656	4.607	0.011	0.975	0.490
C16	4.861	4.787	4.714	0.005	0.995	0.737
C17	4.858	4.779	4.700	0.014	0.974	0.789
C18	4.941	4.838	4.736	0.016	0.973	1.028
C19	4.860	4.788	4.716	0.016	0.965	0.719
C20	4.827	4.770	4.712	0.005	0.996	0.576
C24	4.849	4.766	4.684	0.018	0.963	0.828
C25	4.520	4.451	4.382	0.006	0.992	0.690

General equations of density as a function of sulfur content and matte grade were calculated from the values above for each of the three temperatures. The equations are:

$$D_{1100} = 6.756 - 0.0927\ S + 0.0105\ G \qquad SD = 0.0523 \qquad ..12$$

$$D_{1200} = 6.605 - 0.0884\ S + 0.0099\ G \qquad SD = 0.0465 \qquad ..13$$

$$D_{1300} = 6.465 - 0.0845\ S + 0.0093\ G \qquad SD = 0.0454 \qquad ..14$$

where:

D_{1100} = density in g/mL at 1100°C
D_{1200} = density in g/mL at 1200°C
D_{1300} = density in g/mL at 1300°C
S = mass % sulfur
G = matte grade (mass % copper and nickel)
and SD = standard deviation in g/mL from density values in Table 3.

The densities of the matte specimens at each of the three temperatures, along with iso-density lines determined using the above equations, are shown in Figures 22, 23 and 24. The numbers beside each composition point in the Figures are: (Density - 4.00) x 100. Also, an overall empirical equation of density in g/mL, as a function of sulfur content, matte grade, and temperature has been calculated from the raw data, and is shown below.

$$D = 6.532 - 0.0856\ S + 0.0097\ G + 0.00049\ (1200-t) \qquad ..15$$

The standard deviation of Equation 15 is 0.0496 g/mL.

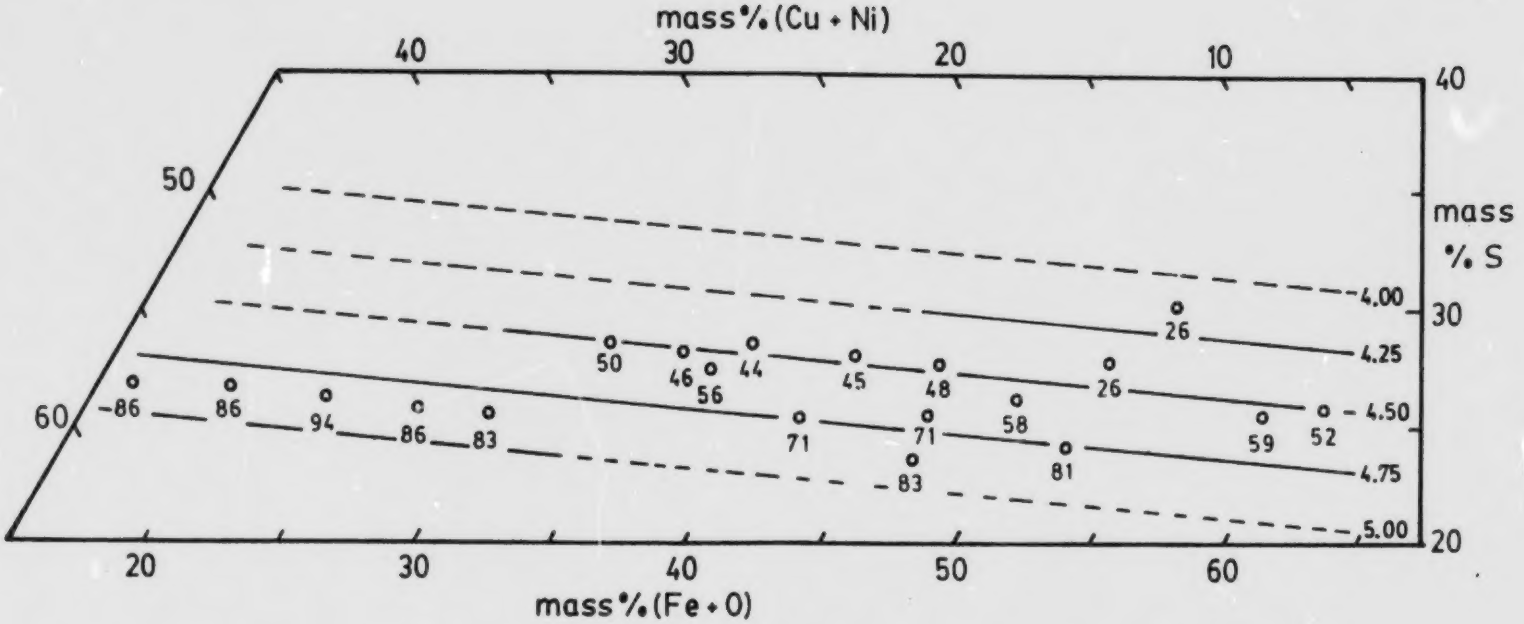


Figure 22. Densities of the matte specimens at 1100°C.

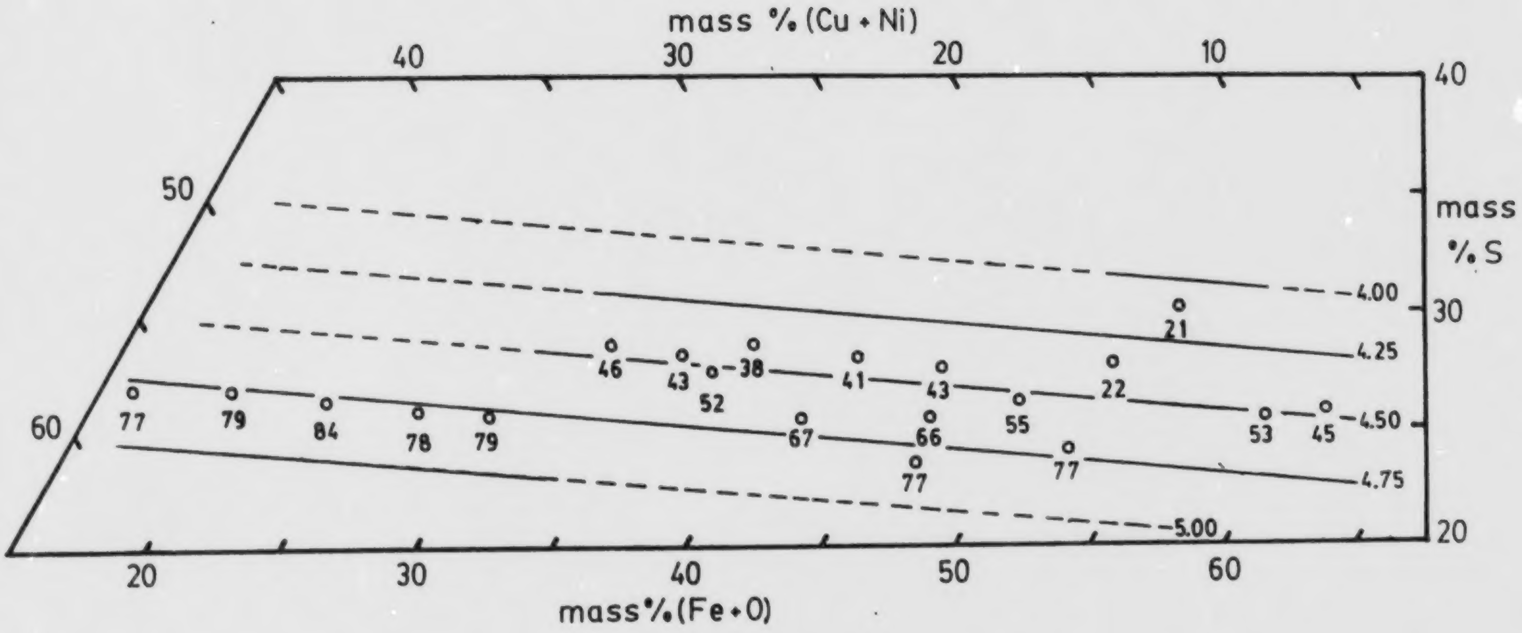


Figure 23. Densities of the matte specimens at 1200°C.

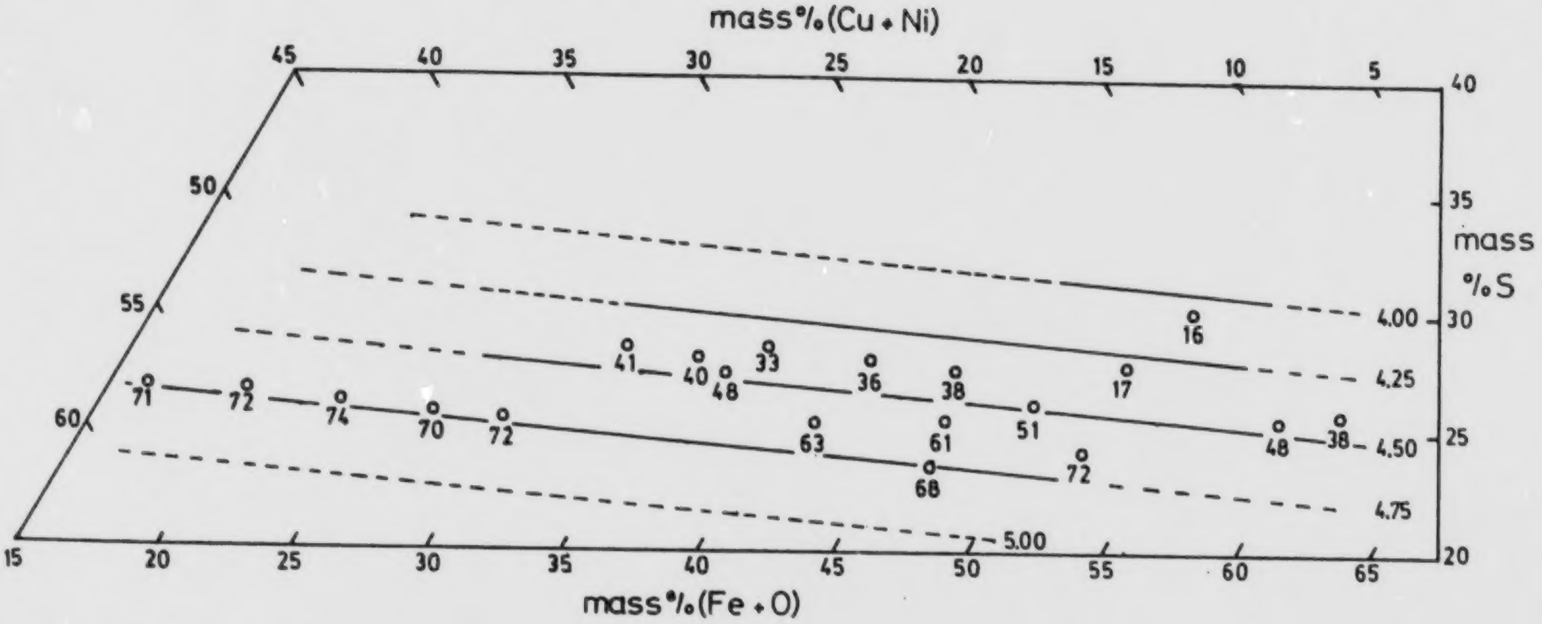


Figure 24. Densities of the matte specimens at 1300°C.

DISCUSSION

Archimedes' principle, when modified to a bottom weighing technique, is an effective method to determine accurately and precisely the densities of molten mattes. The accuracy of the method is enhanced because surface and interfacial effects, associated with the measurements, are eliminated. As outlined previously, these effects can substantially reduce the accuracy of the data obtained in using other methods. Other major factors that can affect the accuracy of the data are: the uncertainty of the matte volume displaced by the bobs, the uncertainty that the weight change indicated by the balance is a true indication of the displaced mass of the matte specimen, and the uncertainty of the matte composition whose density is being determined. Minor factors that affect the accuracy of the data to a degree less than the precision of the measurements, such as changes in atmospheric pressure and the earth's gravitational anomaly, will not be discussed.

i) Technique

a) Volume of Alumina Bobs

The volume of the alumina bobs was determined by immersing them into mercury, and measuring the displaced weight on an electronic balance. Because of the high density of mercury, the relative error associated with the weight measurements is small. Also, the weight of displaced air is negligible in calculating the bob volume. Only the volume of the second upper bob must be determined precisely. The volume of the upper bob is deemed to include a small and precise length of the thin alumina rod, so that the bob also has a definite length. Using Equation 9, the volume of the upper bob was determined excluding any surface effect contributions, which arise from the interaction between the mercury surface and the alumina rod. Although the density of pure mercury is well established, it was not known how this density value changes with the absorption of gases into the mercury. The density of the mercury used was determined as accurately and precisely as possible, and with respect to the density of pure mercury, no difference in density was found to six significant digits. Therefore, the density value of pure mercury, as given in the literature, was applicable to the mercury that was used to determine the volume of the alumina bobs.

The bob volumes were also determined by immersion in water, not to increase the precision of the volume, but to determine the extent of porosity in the alumina, since the surface tension of matte is more similar to that of water than mercury. The alumina, from which the bobs were made, had a relative bulk density of 99.8+%, so it was not certain if the matte would flow into the voids in the alumina bobs. Small bubbles on the surface of the bobs would indicate limited porosity. These bubbles were not visible, and, after the density measurements were made, the bobs showed no signs that matte had soaked into them, with the exception of a small amount of matte that soaked into the alumina cement. However, the matte volume that soaked in was small and it was believed that this volume did not cause a significant error in the displaced matte mass to the extent that the measurements would be systematically low, based on the precision of the density data reported.

The volume of the bobs was determined at room temperature to within the error given by the uncertainty of the balance readout for weights 'W_3' and 'W_4'. The volume of the bobs at high temperatures, however, was calculated using the value of the linear coefficient of thermal expansion of alumina ($LCTE_a$), as stated by the manufacturers. If this value was significanty in error, then there could be some systematic error involved with the volume of the bobs at high temperatures. Although the $LCTE_a$, as stated by the manufacturers, was not checked, this value would have to have been in error by about 1% in order to cause errors in excess of the stated precision, and it is unlikely that the degree of error in the $LCTE_a$ was greater than 1%.

b) Measurements

The typical balance readout as a function of the depth of bob immersion is shown in Figure 25. The force on the balance first decreases as the bob comes in contact with the matte surface. This is caused by the meniscus as it is drawn up to the bob. As the first bob is further immersed, the force due to the meniscus decreases as the contact angle of the bob to the surface increases. At the same time, the weight of the displaced matte increases, and the net force on the balance begins to increase. As the first bob becomes almost totally immersed, the net force on the balance is comprised of the weight of the displaced matte and the now maximum force exerted by the meniscus as the contact angle becomes almost 180°. When the first bob becomes totally submersed, the net force on the balance decreases as the force of the surface effect sharply decreases. The force of the surface effect now is due only to the interaction of the thin alunima rod with the surface. This force does not change as the bob assembly is further lowered into the specimen. The net force on the balance increases slowly as the weight of the displaced mass increases. When the second bob comes in contact with the matte surface, the net force on the balance undergoes the same changes as with the first bob. When both bobs become totally submersed, the net force on the balance consists of a small surface effect due to the alumina rod, and the weight of displaced matte. When both

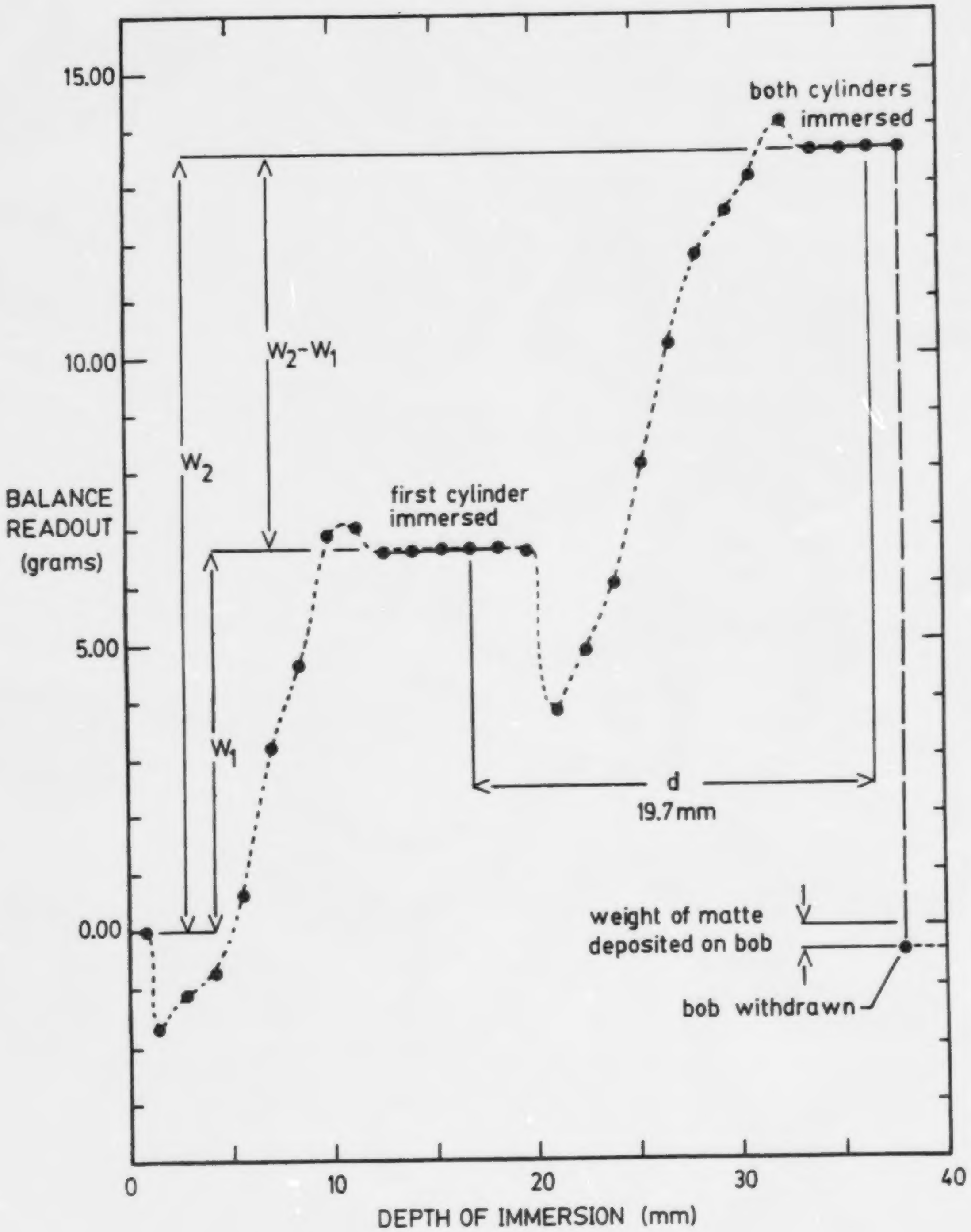


Figure 25. Balance readout versus bob immersion depth.

bobs are withdrawn from the matte, the net negative weight change is due to the matte that was deposited on the alumina bobs. This net weight change becomes zero if the bob assembly is immersed and withdrawn a second time.

The selected measurements were those that bracketed the main displacement body of the second bob, and at a specific length. The difference of these values does not contain a net surface effect contribution. In order to increase the accuracy of these values, a segment of the rod had to be included, even though this contribution is small in comparison to the large volume of the second bob. The measurements were made two or three times at each temperature, and, most often, these values were equal. The only instance where corrections were made to these values was when there was substantial sulfur evolution from the matte specimen. In that case, the rate of sulfur evolution was assumed to be constant with time at one temperature, and the appropriate amount of weight was added to the measurements, respecting the time at which the measurements were taken.

Measurements were discarded only when it was certain that they did not reflect the true displaced mass. An example of this would be when, at lower temperatures, the net weight loss would consistenty increase with each immersion and withdrawl sequence. It was assumed that this indicated that some solidification of the matte was occurring and solid matte was becoming attached to the alumina bobs. Otherwise, all data points obtained were used.

c) Errors in the Measurements

Several factors could affect the accuracy of the measured weights indicated by the balance. One of these is lift on the crucible by the argon gas. The crucible containing the matte specimen sits on the supporting platform in the furnace hot zone. As argon gas flows by from beneath it, it gives the crucible a slight lift, which decreases the force on the balance. But because the argon flowrate is low at the time the measurements are being taken, the effect of this lift is not noticeable to the precision of the balance readout. The magnitude of this lift was checked by momentarily stopping the argon gas flowrate and observing any weight change on the balance readout. It was found that this source of error was negligible.

Another source of error arises from the fact that the density of argon at the matte temperature was not added to the calculated matte density in Equation 11. As is turns out, the density of argon is just less than the precision to which the density data are given. Therefore, adding the value of the argon density to the calculated matte densities would not increase their accuracy.

A more significant source of error is that associated with the surface effect. The value of the surface effect could be calculated from Equation 7, since the volume of the first lower bob was known. But because of the relative magnitudes involved, the surface effect could be calculated only to within a 60% error. Nevertheless, the magnitude of the surface effect can lead to errors in the order of 0.03 g/mL in the calculated matte densities. This could have been a substantial error if it was not eliminated in this technique.

The last source of error in the recorded weight measurements is with the balance itself. Although the balance was calibrated by Fisher Scientific Co. Ltd., the calibration was checked prior to use. This was necessary because the weighing mechanism was not always perpendicular to the force of gravity. The manufacturer states that the deviation in the balance readout, with the balance inclined by 1:1000, is within 0.01 grams. When standard masses were placed into the crucible and weighed at various inclinations and altitudes, the balance reads between 99.96% and 100.04% of the actual mass. At a particular inclination, the deviation was always linear. The inclination of the balance, which is indicated by a bubble type circular level mounted in the balance housing, was never allowed to exceed the degree which gave an error of 0.04%, which corresponds to a mass error of 0.003 grams in '$(W_2-W_1)/g$' in Equation 11. The balance has a reproducibility of 0.005 grams and a readability of 0.01 grams. This gives a total error in '$(W_2-W_1)/g$' of 0.023 grams. This value, combined with an error of 0.02 grams in '$(W_4-W_3)/g$', an error of 2 C^o in 't', and a 1% error in '$LCTE_a$', gives an estimated maximum absolute weight related error of 0.020 g/mL in 'D_{matte}' using Equation 11.

ii) Specimen Compositions

a) Initial Compositions

The B-series matte specimens were prepared by Falconbridge Ltd., using electric furnace matte as the starting material. As was previously mentioned, these specimens contained small amounts of cobalt. Because the density of cobalt sulfide is similar to that of iron sulfide, and because chemically, cobalt behaves similarly to iron in these mattes, it was decided to group the cobalt and iron assays together and to treat them as iron. This is justified because the cobalt assay is so small in comparison to the iron content.

The C-series specimens contained copper, nickel, iron, sulfur, and oxygen. The effect on the matte density by other elements in these specimens, originating from impurities in the starting materials, is negligible because of their very low concentrations. The major impurity in the specimens is expected to be silica, arising from the imperfect separation of the sulfides from the pyrex tubes. Because the solubility of silica in mattes is small, and no silica type second phase was visible in the solidified mattes, the silica concentration in the matte specimens must have been very small. Therefore, the effect on the matte specimen density by the silica is expected to be negligible.

The C-series specimens were synthesized into matte just prior to determining their density in the furnace. The extent of sulfur evolution during fusion was minimized because of the way the sulfur was distributed among the three sulfides. Using the calculated metal- sulfur phase diagrams determined by Sharma and Chang(18,19,20), the sulfur potentials of the three sulfides mixtures were made as similar to one another as possible. This minimized any preferential sulfur evolution from the sulfide with a higher sulfur potential, which could result in an excessively sulfur deficient matte specimen.

b) Changes in Matte Composition

The uncertainty of the matte composition depends on several factors. The most important of these is the change in specimen composition due to sulfur evolution from the matte in the furnace. With the bottom weighing technique, however, the extent of sulfur evolution was determined, since the weight of the matte specimen is continuously being monitored by the balance. In all cases, the change in the sulfur assay during the measurements was within the precision given in Tables 1 and 2.

The matte composition could also be affected by a chemical reaction between the matte and alumina crucible and bobs. The extent of intergranular corrosion of the alumina was minor, since the matte penetrated the alumina to a depth less than 0.1 mm. The matte did, however, partially soak through the Aremco Ceramabond alumina cement on the bob assembly. But because the quantity of matte absorbed was small, it was assumed that the composition of the matte specimen did not change nearly enough to affect the assays reported in Tables 1 and 2.

The last factor that could affect the composition of the specimen in the furnace is the oxidation or deoxidation of the matte by the argon cover gas. The oxygen in the argon was gettered by copper at 450°C to an oxygen partial pressure of about 10^{-10} atmospheres. With the specimen outside the furnace, the furnace atmosphere was purged with the deoxidized argon. When the specimen was raised into the furnace hot zone, the oxygen potential of the surrounding gas was already low. Excess oxygen would oxidize the sulfur in the specimen primarily to SO_2, which would escape as gas and decrease the force on the balance. Oxygen could also dissolve into the matte and thereby increase the force on the balance, if the oxygen potential of the matte was very low. Because the oxygen level in the matte specimens was fixed either by magnetite (in C-series specimens) or by air (in B-series specimens) to values typically found in industrial mattes, it is highly unlikely that a significant amount of oxygen from the surrounding gas would be able to dissolve into these matte specimens. And because the sulfur partial pressure in these mattes is in the same order of magnitude as the oxygen partial pressure, sulfur oxidation would occur prior to specimen deoxidation. Therefore, when no weight change is being recorded by the balance, no oxidation or deoxidation of the specimen is ocurring to a significant degree.

c) Sampling Methods

It is believed that the greatest error in the matte specimen compositions stems from the sampling method. The first thirteen matte specimens (B-series) were sampled by grinding the entire specimen and removing a representative matte sample. The assays of these samples appear to be accurate. However, the remaining seven specimens (C-series) were sampled by removing several central portions of the solidified matte, grinding them and obtaining representative samples. It was later determined that during solidificaion, oxygen, in the form of magnetite, preferentially collected on the matte specimen surface in a thin layer. Because this surface was excluded during sampling of these mattes, the oxygen assay determined was about 50% low, based on the amount of oxygen that was added to the specimens. This was especially true for the specimens with relatively high oxygen contents since the initial oxygen level of these synthesized mattes was known fairly accurately.

iii) Matte Density as a Function of Temperature and Composition

The densities of the matte specimens were calculated using Equation 11. From these values, the density of each specimen composition was determined at 1100°C, 1200°C, and 1300°C using linear regression. Because of the relatively few data points at each composition, the inherent scatter of the data, and the relatively narrow temperature range that was investigated, it was not possible to determine generally if the matte specimen density was other than a linear function of temperature. Because the correlation coefficient, R, is not far from 1, and the standard error of estimate in Table 3 (0.003 to 0.018 g/mL) is less than the estimated experimental error (0.020 g/mL), it appears that the assumption of linear temperature dependence, for each specimen composition is justified. The values of Alpha, the temperature coefficient of density in Table 3, vary considerably over the range of composition investigated.

Examination of the data, however does not seem to indicate any significant correlation of Alpha values with either (Cu + Ni) mass % or with S mass %, although because Alpha is small, the relative errors associated with it are large. Nevertheless, Alpha is assumed to be independent of composition.

Using the calculated values of the specimen densities at 1100°C, 1200°C, and 1300°C, Equations 12, 13, and 14 were determined. These general equations, plotted in Figures 22, 23, and 24, can be used to predict the densities of mattes at the above temperatures. The figures show a reasonable fit between the data and Equations 12 - 14, and this is confirmed by the relatively low values of the standard deviation in the equations.

Incorporating temperature as a linear relationship, the empirical Equation 15 is determined. To estimate the matte density at various compositions and temperatures, the empirical equations should be interpolated. Although interpolation of the empirical equation can give fairy accurate density values, extrapolation to values outside the composition and temperature ranges investigated can be misleading because of the uncertainty in the accuracy of Equation 15.

CONCLUSIONS

1. The bottom-weighing technique based on Archimedes' principle is a superior method to determine densities of molten mattes because surface and interfacial tension effects are eliminated.

2. At constant matte grade, sulfur in mattes decreases the density by 0.0856 g/mL per 1 mass % S, while at constant sulfur content, copper and nickel increase the density of the matte by 0.0097 g/mL per 1 mass % (Cu + Ni).

3. The temperature coefficient of density is similar over the range of compositions investigated and corresponds to a decrease of 0.00049 g/mL/C° in the range 1100°C - 1300°C.

4. The empirical equation for density of mattes as a function of composition and temperature was determined by linear regression to be:

$$\text{Density} = 6.532 - 0.0856\ \%\text{S} + 0.0097\ \%(\text{Cu} + \text{Ni}) + 0.00049\ [1200 - t(\text{C}^{\circ})]$$

5. The analytical error of each data point was estimated at 0.02 g/mL absolute. The standard deviation of the empirical equation is 0.05 g/mL.

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APPENDICIES

APPENDIX A - Initial Compositions of B-series Specimens

SPECIMEN NUMBER	ASSAY (mass %)						
	Cu	Ni	Co	Fe	S	O	TOTAL
B3	15.5	15.3	0.53	34.0	26.5	3.9	95.73
B6	8.2	8.4	0.11	49.0	28.0	3.1	96.81
B7	9.1	9.3	0.11	46.0	29.2	2.9	96.61
B12	11.4	13.0	----	45.0	25.3	2.5	97.2
B13	12.7	13.5	----	42.0	27.4	2.5	98.1
B14	14.0	14.9	----	39.0	28.0	2.3	98.2
B16	16.5	16.2	0.10	33.0	28.3	3.1	97.20
B17	16.1	15.3	0.10	38.0	25.0	2.6	97.10
B18	16.9	17.9	0.10	34.0	27.3	2.2	98.40
B19	18.3	18.7	0.08	30.0	28.0	1.9	96.98
B20	7.4	7.7	0.15	54.0	25.1	3.6	97.95
B21	11.9	11.4	0.12	47.0	24.3	2.9	97.62
B22	13.7	13.9	0.11	42.0	24.4	2.7	96.81

APPENDIX B - Target Compositions of C-series Specimens

SPECIMEN NUMBER	TARGET COMPOSITIONS (MASS %) Cu	Ni	Fe	S	O
C 16	21.35	21.35	30.4	25.0	1.9
C 17	22.80	22.80	27.2	25.5	1.7
C 18	24.25	24.25	24.0	26.0	1.5
C 19	25.70	25.70	20.8	26.5	1.3
C 20	27.15	27.15	17.6	27.0	1.1
C 24	14.10	14.10	46.4	22.5	2.9
C 25	6.30	6.30	59.2	24.5	3.7

On a 250 gram basis, the amount of starting materials, in grams, required to synthesize the metal sulfides is shown below. The sulfides are then combibed with magnetite to form the specimens.

SPEC.:	C16	C17	C18	C19	C20	C24	C25
Copper-sulfur mixture:							
Cu	53.375	57.000	60.625	64.250	67.875	35.250	15.750
S	13.469	14.384	15.299	17.892	21.663	8.895	3.974
Nickel-sulfur mixture:							
Ni	53.375	57.000	60.625	64.250	67.875	35.250	15.750
S	19.432	20.752	22.072	23.392	24.711	12.833	5.734
Iron-sulfur mixture:							
Fe	63.564	56.874	50.183	43.493	36.800	97.019	123.783
S	29.599	28.614	27.629	24.966	21.126	34.522	51.542
Magnetite:							
Fe_3O_4	17.185	15.376	13.567	11.758	9.949	26.230	33.466

APPENDIX C - Final Assays of Matte Specimens

SPECIMEN NUMBER	ASSAY (mass %) Cu	Ni	Co	Fe	S	O	TOTAL
B3	18.0	17.7	0.61	33.2	28.2	1.79	99.50
B6	8.4	8.5	0.10	50.4	30.6	3.57	101.57
B7	9.8	10.0	0.11	47.2	27.1	3.29	97.50
B12	11.9	12.3	0.12	46.3	25.9	2.29	98.81
B13	13.0	13.3	0.12	42.6	27.3	2.35	98.67
B14	14.5	14.9	0.10	39.9	28.0	2.27	99.67
B16	16.4	16.6	0.08	35.9	28.6	2.02	99.60
B17	16.1	16.7	0.10	39.4	25.3	1.87	99.47
B18	17.2	17.8	0.09	35.2	27.4	1.85	99.54
B19	18.8	19.2	0.07	31.2	28.4	1.54	99.21
B20	7.5	8.0	0.15	54.7	25.2	3.30	98.75
B21	11.4	12.1	0.12	49.4	24.0	2.12	99.14
B22	13.9	14.1	0.12	43.9	25.4	2.09	99.51

SPECIMEN NUMBER	ASSAY (mass %) Cu	Ni	Fe	S	O	TOTAL
C16	21.66	22.35	28.55	25.32	1.20	99.08
C17	23.38	23.22	25.80	25.77	1.38	99.55
C18	25.04	24.78	22.60	26.20	0.97	99.59
C19	26.19	26.72	19.30	26.50	0.59	99.30
C20	26.48	30.18	15.75	26.65	0.43	99.51
C24	14.61	14.45	44.25	23.18	1.71	98.20
C25	6.45	6.49	57.30	25.12	2.12	97.48

APPENDIX D - Raw Data

$(W_4-W_3)/g$ grams	t C^o	W_1/g grams	W_2/g grams	$(W_2-W_1)/g$ grams	D_{matte} g/mL
specimen no:	B3				
22.29	1310	7.03	14.52	7.49	4.406
21.86	1305	7.01	14.35	7.34	4.403
21.86	1306	7.03	14.35	7.33	4.397
21.86	1231	7.10	14.46	7.36	4.423
21.86	1232	7.11	14.46	7.36	4.423
specimen no.:	B6				
22.13	1310	6.69	13.66	6.97	4.130
22.13	1308	6.73	13.74	7.01	4.154
22.13	1243	6.78	13.84	7.06	4.190
22.13	1239	6.78	13.86	7.08	4.202
22.13	1178	6.81	13.91	7.10	4.221
22.13	1178	6.82	13.92	7.10	4.221
22.13	1120	6.84	13.96	7.14	4.251
22.13	1120	6.83	13.98	7.15	4.247
22.13	1077	6.86	14.01	7.15	4.261
22.13	1076	6.85	14.01	7.16	4.267
specimen no.:	B7				
22.13	1307	6.70	13.73	7.03	4.165
22.13	1241	6.75	13.82	7.07	4.196
22.13	1241	6.75	13.83	7.08	4.202
22.13	1184	6.80	13.91	7.11	4.226
22.13	1184	6.80	13.91	7.11	4.226
22.13	1136	6.82	13.95	7.13	4.243
22.13	1135	6.82	13.95	7.13	4.243
22.13	1077	6.85	14.02	7.17	4.273
22.13	1077	6.84	14.00	7.16	4.267
specimen no.:	B12				
21.61	1318	----	-----	7.43	4.507
21.61	1249	----	-----	7.46	4.533
21.61	1198	----	-----	7.46	4.539
21.61	1145	----	-----	7.49	4.563
21.61	1087	----	-----	7.52	4.588

$(W_4-W_3)/g$ grams	t C^o	W_1/g grams	W_2/g grams	$(W_2-W_1)/g$ grams	D_{matte} g/mL
specimen no.:	B13				
21.92	1306	7.06	14.40	7.34	4.391
21.92	1310	7.16	14.45	7.29	4.361
21.92	1309	7.14	14.44	7.30	4.367
21.92	1248	7.17	14.53	7.36	4.409
21.92	1246	7.17	14.54	7.37	4.416
21.92	1192	7.19	14.61	7.42	4.452
21.92	1191	7.19	14.59	7.40	4.440
21.92	1137	7.22	14.63	7.41	4.452
21.92	1137	7.18	14.62	7.44	4.470
21.92	1083	7.23	14.68	7.45	4.482
21.92	1083	7.21	14.67	7.46	4.488
specimen no.:	B14				
21.92	1301	7.10	14.40	7.30	4.368
21.92	1299	7.12	14.40	7.28	4.356
21.92	1216	7.19	14.52	7.33	4.395
21.92	1216	7.17	14.52	7.35	4.407
21.92	1152	7.21	14.59	7.38	4.432
21.92	1154	7.20	14.58	7.38	4.432
21.92	1079	7.26	14.66	7.40	4.452
21.92	1076	7.24	14.65	7.41	4.459
specimen no.:	B16				
22.29	1318	6.85	14.19	7.34	4.317
22.29	1318	6.89	14.22	7.33	4.311
22.29	1318	6.89	14.26	7.37	4.334
22.29	1245	6.98	14.40	7.42	4.372
22.29	1243	6.98	14.36	7.38	4.348
22.29	1243	6.98	14.36	7.38	4.348
22.29	1187	7.02	14.48	7.46	4.402
22.29	1186	7.06	14.47	7.41	4.372
22.29	1185	7.02	14.46	7.44	4.390
22.29	1130	7.05	14.50	7.45	4.402
22.29	1129	7.03	14.53	7.50	4.432
22.29	1128	7.03	14.53	7.50	4.432
22.29	1073	7.09	14.61	7.52	4.450
22.29	1073	7.07	14.60	7.53	4.456
22.29	1072	7.07	14.64	7.57	4.480

$(W_4-W_3)/g$ grams	t C^o	W_1/g grams	W_2/g grams	$(W_2-W_1)/g$ grams	D_{matte} g/mL
specimen no.:	B17				
21.98	1302	7.48	15.25	7.77	4.636
21.98	1302	7.52	15.29	7.77	4.636
21.98	1302	7.53	15.28	7.75	4.624
21.98	1231	7.58	15.37	7.79	4.656
21.98	1230	7.57	15.34	7.77	4.644
21.98	1176	7.58	15.41	7.83	4.687
21.98	1175	7.59	15.38	7.79	4.663
21.98	1122	7.61	15.45	7.84	4.699
21.98	1121	7.60	15.45	7.84	4.699
21.98	1060	7.62	15.49	7.87	4.724
21.98	1058	7.63	15.50	7.87	4.725
specimen no.:	B18				
21.94	1319	7.26	14.75	7.49	4.475
21.94	1319	7.27	14.76	7.49	4.475
21.94	1250	7.34	14.86	7.52	4.501
21.94	1250	7.33	14.83	7.50	4.489
21.94	1192	7.38	14.92	7.54	4.519
21.94	1191	7.35	14.90	7.55	4.526
21.94	1135	7.40	14.96	7.56	4.538
21.94	1134	7.37	14.96	7.59	4.556
21.94	1086	7.39	14.99	7.60	4.568
21.94	1086	7.37	14.98	7.61	4.574
specimen no.:	B19				
21.83	1309	7.09	14.40	7.31	4.391
21.83	1309	7.18	14.53	7.35	4.415
21.83	1310	7.20	14.55	7.35	4.415
21.83	1309	7.21	14.53	7.32	4.397
21.83	1245	7.26	14.64	7.38	4.440
21.83	1244	7.27	14.65	7.38	4.440
21.83	1244	7.26	14.65	7.39	4.446
21.83	1190	7.32	14.76	7.44	4.482
21.83	1190	7.33	14.74	7.42	4.470
21.83	1190	7.35	14.77	7.42	4.470
21.83	1135	7.38	14.83	7.45	4.494
21.83	1135	7.37	14.81	7.44	4.488
21.83	1135	7.38	14.81	7.43	4.482
21.83	1077	7.43	14.89	7.46	4.507
21.83	1075	7.41	14.86	7.45	4.501
21.83	1077	7.40	14.87	7.47	4.513

(W_4-W_3)/g grams	t C^o	W_1/g grams	W_2/g grams	(W_2-W_1)/g grams	D_{matte} g/mL
specimen no.:	B20				
21.77	1298	7.07	14.45	7.38	4.446
21.77	1296	7.21	14.69	7.48	4.507
21.77	1297	7.21	14.66	7.45	4.488
21.77	1235	7.27	14.75	7.48	4.514
21.77	1236	7.27	14.76	7.49	4.520
21.77	1235	7.27	14.75	7.48	4.514
21.77	1178	7.32	14.81	7.49	4.526
21.77	1178	7.30	14.80	7.50	4.532
21.77	1178	7.30	14.82	7.52	4.544
21.77	1119	7.30	14.89	7.59	4.593
specimen no.:	B21				
20.51	1299	7.27	14.64	7.37	4.713
20.51	1301	7.34	14.74	7.40	4.732
20.51	1300	7.34	14.73	7.39	4.725
20.51	1233	7.49	14.90	7.41	4.746
20.51	1232	7.40	14.83	7.43	4.759
20.51	1182	7.42	14.87	7.45	4.778
specimen no.:	B22				
21.89	1322	7.57	15.25	7.68	4.599
21.89	1321	7.54	15.23	7.69	4.605
21.89	1250	7.59	15.30	7.71	4.625
21.89	1249	7.59	15.32	7.73	4.637
21.89	1190	7.61	15.34	7.73	4.644
21.89	1192	7.61	15.37	7.76	4.662
21.89	1131	7.63	15.40	7.77	4.675
21.89	1131	7.63	15.42	7.79	4.687
21.89	1079	7.62	15.46	7.84	4.723
21.89	1079	7.62	15.47	7.85	4.729
specimen no.:	C16				
21.31	1301	7.37	15.03	7.66	4.714
21.31	1299	7.36	15.01	7.65	4.708
21.31	1299	7.37	15.04	7.67	4.721
21.31	1227	7.44	15.17	7.73	4.766
21.31	1227	7.44	15.17	7.73	4.766
21.31	1166	7.49	15.28	7.79	4.810
21.31	1165	7.51	15.31	7.80	4.817

(W_4-W_3)/g grams	t C°	W_1/g grams	W_2/g grams	(W_2-W_1)/g grams	D_{matte} g/mL
specimen no.:	C17				
22.14	1290	7.57	15.48	7.91	4.687
22.14	1293	7.53	15.50	7.97	4.722
22.14	1290	7.56	15.53	7.97	4.722
22.14	1220	7.58	15.58	8.00	4.748
22.14	1218	7.60	15.62	8.02	4.761
22.14	1160	7.64	15.73	8.09	4.809
22.14	1160	7.63	15.73	8.10	4.815
22.14	1107	7.70	15.86	8.16	4.857
specimen no.:	C18				
22.73	1311	7.44	15.63	8.19	4.724
22.73	1313	7.45	15.65	8.20	4.730
22.73	1312	7.49	15.67	8.18	4.718
22.73	1251	7.54	15.79	8.25	4.766
22.73	1249	7.53	15.83	8.30	4.795
22.73	1197	7.60	15.93	8.33	4.819
22.73	1200	7.64	16.03	8.39	4.853
22.73	1198	7.65	16.06	8.41	4.865
22.73	1138	7.70	16.15	8.45	4.896
specimen no.:	C19				
22.20	1312	7.60	15.55	7.95	4.695
22.20	1311	7.58	15.57	7.99	4.719
22.20	1231	7.68	15.72	8.04	4.758
22.20	1231	7.69	15.76	8.07	4.776
22.20	1174	7.69	15.82	8.13	4.818
22.20	1172	7.72	15.81	8.09	4.795
specimen no.:	C20				
22.20	1302	7.66	15.63	7.97	4.708
22.20	1303	7.69	15.66	7.97	4.708
22.20	1235	7.77	15.80	8.03	4.752
22.20	1236	7.75	15.79	8.04	4.757
22.20	1175	7.83	15.89	8.06	4.777
22.20	1174	7.83	15.91	8.08	4.789
22.20	1121	7.87	15.98	8.11	4.813
22.20	1123	7.84	15.95	8.11	4.813
22.20	1073	7.89	16.05	8.16	4.848
22.20	1066	7.84	15.99	8.15	4.843

$(W_4-W_3)/g$	t	W_1/g	W_2/g	$(W_2-W_1)/g$	D_{matte}
grams	C°	grams	grams	grams	g/mL
specimen no.:	C24				
21.22	1324	7.58	15.09	7.51	4.639
21.22	1323	7.58	15.13	7.55	4.664
21.22	1269	7.62	15.24	7.62	4.713
21.22	1267	7.63	15.25	7.62	4.713
21.22	1219	7.68	15.38	7.70	4.769
21.22	1218	7.71	15.42	7.71	4.775
21.22	1168	7.74	15.46	7.72	4.787
21.22	1169	7.75	15.49	7.74	4.800
21.22	1116	7.78	15.53	7.75	4.812
specimen no.:	C25				
21.67	1308	7.08	14.30	7.22	4.369
21.67	1306	7.13	14.38	7.25	4.387
21.67	1306	7.11	14.34	7.23	4.375
21.67	1235	7.16	14.46	7.30	4.425
21.67	1233	7.16	14.47	7.31	4.432
21.67	1169	7.24	14.60	7.36	4.469
21.67	1168	7.27	14.64	7.37	4.475

FALCONBRIDGE

TO DEVELOP A CLEAN SMELTING PROCESS FOR HIGHLY ROASTED COPPER-NICKEL CALCINES AND TO IMPROVE METAL RECOVERY

PART C: METALLIC PHASE SATURATION BOUNDARY IN THE Ni-Cu-Fe-S SYSTEM BETWEEN 1000 AND 1300°C

by

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EXECUTIVE SUMMARY

The Falconbridge plant was originally designed for the removal of 50% of the sulphur entering the roasters. In order to reduce SO_2 emissions further, the smelter has recently increased the degree of roast to 60%. This allows more of the sulphur entering the fluidized bed roasters to be fixed as sulphuric acid, a saleable by-product.

When the degree of roast is increased, however, more heavily oxidized calcines are produced. This results in higher matte grades in the electric furnace which is detrimental to smelter metal recoveries. The countermeasure is to smelt under more intensive reducing conditions. In the presence of coke, however, a dense metallic phase forms during the smelting of the calcine. This leads to a buildup of metal on the furnace hearth, thus, reducing the capacity of the furnace and interfering with the tapping operation.

From an industrial perspective, it is desirable to ascertain the location of the matte-metal saturation boundary. For example, this boundary represents a condition of minimum oxygen potential at which point slag losses of nickel and cobalt are at their lowest.

A laboratory study was initiated in order to yield matte-metal equilibration data at temperatures ranging from 1000 to 1300°C. The compositions of the mattes (Ni, Cu, Fe, S) were in the range encountered in Falconbridge matte smelting utilizing increased degrees of roast.

The liquidus compositions and the tie-lines between the solid alloys and the liquid sulphide phases were obtained. The effect of different Ni/Cu ratios on the experimental results was examined.

SOMMAIRE

L'usine de Falconbridge a été conçue pour supprimer 50% du soufre dans les fours de grillage. Afin de réduire davantage les émissions de SO_2, la fonderie a récemment augmenté a 60% le taux de grillage. Ceci permet à une grande quantité de soufre dans le four à lit fluidisé d'être fixée en acid sulfurique, un sous-produit vendable.

L'augmentation du taux de grillage produit des calcinés à haute oxydation donnant lieu à des mattes de meilleure qualité dans les fours électriques. Ceci se fait au détriment du rendement métal de la fonderie. La contre-mesure consiste en la fonte de minerais dans des conditions de réduction plus intenses. Cependant, en présence du coke, il se forme une phase métallique dense lors de la fusion des calcinés, ce qui cause une accumulation de métal au sole du four diminuant la capacité du four et nuisant à la coulée.

Dans une perspective industrielle, il est souhaitable d'établir le seuil de saturation des mattes-métaux. Par exemple, ce seuil représente les conditions de potentiel en oxygène minimal dans lesquelles les pertes en laitier de nickel et de cobalt sont les moins importantes.

Une étude en laboratoire a été effectuée afin de déterminer les données des mattes-métaux équilibrées à des températures de 1000 à 1300°C. Les compositions des mattes (Ni, Cu, Fe, S) se situaient dans les limites obtenues lors de la fusion de mattes à des températures plus élevées de grillage à l'usine de Falconbridge.

Les compositions liquidus et les lignes d'équilibre entre les alliages solides et les phases de sulfure liquide ont été obtenues. De plus, les effets de différents rapports nickel/cuivre sur les données expérimentales on été étudiés.

TABLE OF CONTENTS

PAGE

EXECUTIVE SUMMARY

SOMMAIRE

BACKGROUND 1

LABORATORY STUDY OBJECTIVES 1

EQUIPMENT 2

  Furnace and Controller 2
  Electron Probe Microanalyser 2

MATERIALS 2

  Ferronickel Alloys 2
  FeS 3
  Metal Powders 3
  Ni_3S_2 3
  Cu_2S 3

PROCEDURE 3

  Melt Compositions 3
  Charge Preparation 4
  Furnace and Sample Treatment 4

RESULTS 4

  Preliminary Results 4
  Equilibration Studies 5

DISCUSSION 6

  Matte-Metallics Saturation in Ni, Cu, Fe Mattes 6

REFERENCES 9

DATA AND FIGURES 10

BACKGROUND

The 'Falconbridge Smelter Environmental Improvement Program' was initiated in 1978. The process circuit consists of slurry-fed fluid bed roasters for partial roasting of a nickel-copper concentrate, electric furnaces for smelting the calcine, and matte converters. The plant was originally designed to remove 50% of the sulphur entering the roasters. Under the new Environmental Improvement Program, this has been increased to 55-60%. Increasing the degree of roast results in a decrease in SO_2 emissions because more of the sulphur can be converted to sulphuric acid.

When the degree of roast is increased, more heavily oxidized calcines are produced and this results in higher matte grades in the electric furnace. Both of these effects are detrimental to smelter metal recoveries. The counter-measure is to smelt under more intensive reducing conditions. In the presence of coke, however, a metallic phase may form during the smelting of the calcine. The use of reductants to smelt partially roasted calcines lowers the sulphur level and matte grade, shifting the matte composition to the point where metallic precipitation may occur. The metallic phase has a density that is higher than the matte's. This can lead to a buildup of metal on the furnace hearth. Also, at the lower temperatures at the bottom of the furnace, metallics can precipitate from the matte.

The metallic phase saturation boundary of matte is a practical limit to furnace operations beyond which metal builds up on the hearth. The saturation boundary, however, also represents a condition of minimum oxygen potential at which point slag losses of nickel and cobalt are at their lowest. Therefore, the location of the metallic phase saturation boundary is essential to enable operation of the smelting furnace at maximum metal recovery without encountering substantial bottom buildup.

This report constitutes part C of DSS contract OSQ83-00195. It covers an investigation of the metallic phase saturation boundary in Ni-Cu-Fe-S mattes at compositions representative of electric furnace smelting. A laboratory program was initiated in order to determine the composition of mattes in equilibrium with metallics over the temperature range between 1000 and 1300°C. The results of this investigation are presented in this report.

LABORATORY STUDY OBJECTIVES

The laboratory study was initiated in order to yield matte-metal equilibration data at temperatures ranging from 1000 to 1300°C (1273-1573 K). The compositions of the mattes (Ni, Cu, Fe, S) were in the range encountered in Falconbridge matte smelting utilizing increased degrees of roast. The tests were performed in sealed tubes and metallics were added in the form of a ferronickel alloy. The equilibration reaction between matte and metallics resulted in the formation of a new metallic phase in equilibrium with molten matte. The analysis of these mattes and the new metallic phases provided the data necessary to construct tie-lines between the two phases.

The main objective was the estimation of the liquidus temperatures. This information is of value in predicting alloy formation at various temperatures as there is a vertical temperature gradient throughout the electric furnace.

EQUIPMENT

Furnace and Controller

A Marshall resistance-type furnace was used in the high temperature equilibration tests. Specifications on furnace and auxiliary equipment are given as follows:

Furnace:	"Marshall" (1600°C max.) Power - 15KVA - Single Phase Frequency - 60 Hz Maximum Current Draw - 138 A
Controller:	Eurotherm SCR Analog (Model 917) Thermocouple Type "B" actuated (Pt/6% Rh vs Pt/30% Rh)
Heating Elements:	5 Super Kanthal 33"
Heated Chamber:	4-1/8" x 24"
Charge Temperature Measurement:	Thermocouple (Pt vs Pt/10% Rh) Omega Digital Thermometer
Furnace Inner Tube:	Alumina O.D. 3-3/4" I.D. 3-1/4" Length 48"

Electron Probe Microanalyser

Cambridge Mark V electron-probe microanalyser with LINK 860 Energy Dispersive Detector, 20 kV, 10 μA, pure element standards. LINK ZAF4 Data Reduction Software.

MATERIALS

Ferronickel Alloys

High purity Falconbridge Granular Nickel and high purity iron powder were used to prepare a series of ferronickel alloys containing 10 to 60% Ni. The appropriate masses of nickel and iron (50.0 g total) were heated in a fireclay crucible in an induction furnace. The sample was melted, and then maintained at a temperature greater than 1600°C for 5 minutes. The sample was then cooled to room temperature. The solidified melt was ground clean and milled to obtain fine chips.

FeS

Reagent grade FeS was obtained from two suppliers: Sargent-Welch and Fisher Scientific. Oxygen was removed by placing 500 g of material in a pre-heated fireclay crucible and purging with hydrogen (3 l/min) for 30 min. The material was then heated to 1250°C, held at that temperature in a gas fired pot furnace, and subsequently cooled under hydrogen. The final material analysed:

Source	Analysis (mass %)		
	Fe	S	O
Fisher	65.3	31.9	0.74
Sargent Welch	71.8	26.5	0.32

The Fisher material was closer to stoichiometric FeS (i.e. 63.6% Fe). Differences can be attributed to the preparation technique which appears to have resulted in hydrogen sulphide evolution and some metallics formation. The analysis of the 'FeS' was taken into account when preparing the matte samples.

Metal Powders

High purity metal powders included Mond Carbonyl Nickel powder and BDH reagent grade iron powder.

Ni_3S_2

Nickel sulphide (Ni_3S_2) was prepared from carbonyl nickel powder and elemental sulphur. Stoichiometric amounts of nickel and sulphur were mixed, then transferred to a fireclay crucible. The crucible was covered and purged with argon before being heated to 900°C. The ensuing reaction is exothermic, but controlled. The contents of the crucible were cooled under argon and then crushed and ground.

Cu_2S

Reagent grade Cu_2S was used as received.

PROCEDURE

Melt Compositions

A computer spreadsheet program was used to calculate the masses of sulphides and metals needed for each experiment. The program was based on an initial target matte composition. The compositions of the initial sulphides and metals were input, along with the starting mass of Cu_2S (usually 10.0 g). The computer provided sequential calculations of Ni_3S_2, FeS and Fe, as well as the total mass of the matte.

The composition and mass of the ferronickel alloy (usually 10.0 g) were input, and a final overall composition and mass were provided as output by the computer.

Charge Preparation

Quartz tubing (6 mm i.d., 10 mm o.d.) was used in all of the tests. A 40 cm length of tube was sealed at one end using an oxy-acetylene torch. All moisture was removed in order to prevent the dry powders from sticking to the inside wall of the tube.

Ferronickel chips were fed into the tube through a small funnel, followed by the required amounts of Cu_2S, FeS, Ni_3S_2, and Fe powders. The tube was then mounted vertically and connected to a vacuum pump. When the pressure had been reduced to approximately 0.1 mm Hg, the bottom of the tube was slowly rotated, causing the viscous quartz to twist around its own axis. After 4-5 turns, the top of the quartz was shaped into a small hook. This hook was used for suspending the charge in the furnace.

Chromel wire (1.0 mm diameter) was cut into 13 cm lengths. These sections were looped together to form a sample suspension chain. Samples were suspended vertically in the hot zone of the furnace.

Furnace and Sample Treatment

The furnace was controlled at the desired temperature. An argon atmosphere was maintained during the charge treatment period to minimize oxidation of the wire. The sealed specimen was suspended in the hot zone of the furnace for 24-48 hours. The bottom of the furnace was then opened and the suspension wire was cut, allowing the vial to drop into a water quench tank. The shattered quartz was removed and the pins of matte/alloy were recovered and dried at 110^{o}C for 1 hour.

The bottom tip of the charge (containing the alloy) was broken away from the matte. A polished section of the alloy matrix was prepared and analysed for Cu, Ni and Cu by electron probe techniques.

The matte was stage ground to -48 mesh and examined for metallics. Generally, the metallic particles had settled but the occasional metallic particle was removed from the matte. The matte was then ground to -100 mesh and analysed for Ni, Cu, Fe, O and S. Metals were determined by atomic absorption methods. Sulphur and oxygen were determined by combustion procedures (LECO Instruments).

RESULTS

Preliminary Tests

A series of tests was performed in order to determine the optimum residence time in the furnace to obtain a sufficient quantity of the new alloy phase for analysis.

An initial matte mixture was prepared from the following:

Cu_2S	21.88 g
Ni_3S_2	23.86 g
FeS	53.84 g
Fe	1.35 g
	100.93 g

Five ampoules were prepared according to the aforementioned procedure. The matte mixture (6.03 g) and FeNi chips (1.32 g, 20% Ni-80% Fe) were transferred to the quartz tubes. All five ampoules were heated in the furnace at 1100°C, with an ampoule being removed after 3, 6, 15, 24 and 48 hours. Each sample was examined visually and microscopically and the following results were obtained:

Test #	Hours	Notes
1	3	Alloy chips retained original morphology
2	6	Change in composition at the alloy's surface
3	15	Change in alloy composition
4	24	Change in alloy composition
5	48	Majority of metallics as new phase

The tube from test #5 had collapsed. All alloys were, however, separated and mounted as polished sections for scanning. The 48 hour test showed the maximum amount (i.e. thickness) of new alloy phase surrounding the original alloy. The new phase analysed 30% Ni, as compared to 20% for the core alloy. The new alloy thickness was approximately 400 microns and this was more than sufficient for probe analysis.

Owing to the problems associated with the tube collapse, a 24 hour equilibration period was used for subsequent tests at 1100°C. Some tests at 1000°C were performed for 48 hours.

Equilibration Studies

The results of the analysis of 53 matte and alloy samples are given in Table 1. Several samples were not recovered, and due to various factors, some of the alloys could not be analysed. For example, in some cases the grain size was <10 microns, making probe analysis difficult.

The tie-line data from the equilibration studies are presented graphically in Figures 1-4 for 1000, 1100, 1200 and 1300°C, respectively. Tie-lines between the matte and alloy phases run parallel in most cases, however, there are several exceptions. Only a limited number of data points were obtained at 1300°C due to difficulties encountered in recovering the samples.

Attempts were made to minimize oxygen in the mattes - both in the source materials and in the experimental procedures. Oxygen concentrations are in the 1.5% range, and some of this was probably introduced during the sample drying and preparation stages.

The results presented in Figures 1-4 have been normalized to ensure that

$$\sum(Cu+Ni+Fe+S+O)$$

totals 100% for each of the matte samples. The tie-lines are shown connecting the Fe-(Ni+Cu) axes. This assumption was based on the work of Lenz et al. (6). In their study, the sulphur content of the alloy phase contained between 0.04 and 0.06 mass % S. Their tie-lines were drawn connecting the Fe-Ni binary.

DISCUSSION

Matte-Metallics Saturation in Ni, Cu, Fe Mattes

Binary metal-sulphur phase diagrams indicate that on contacting the liquidus curve, a sulphur-free metal will precipitate. Binary metal-sulphur diagrams (Ni-S, Cu-S, Fe-S) are shown in Figures 5-7 (1-3). For the Fe-Ni-S ternary system, shown as a pseudo-binary (Fe/Ni = 1.5) in Figure 8 (4), it can be seen that a sulphur-free ferro-nickel alloy is precipitated on contacting the liquidus. Vanyukov et al. (5) have determined the liquidus in the Fe-Ni-S system. Lenz et al. (6) have constructed tie-lines in the same system at temperatures between 1200 and 1400°C. A computer literature search relating to the quaternary Fe-Ni-Cu-S system was conducted through Dialog Information Services. The only paper of relevance was by Sobolev et al. (7), namely: "Investigation of the Cu-Ni-Fe-S System as Applicable to the Processing of Cu-Ni Ores". A comparison between Sobolev's work and this work will be described later in the text.

An examination of the data presented in Figures 1-4 reveals that there is some scatter in the results. This could be caused by two main factors:

1) analytical errors

2) different Ni/Cu ratios

In the analysis of the mattes (Table 1), the $\sum(Cu+Ni+Fe+S+O)$ quantity ranged between 93.40 to 102.75%. This gives an indication of the difficulties encountered in analysing the various components of a matte sample.

The effect of different Ni/Cu ratios would also be expected to influence the location of the data points on a ternary diagram when Ni+Cu are combined as a single component. For example, consider the results presented in Figure 9. In general, it can be seen that for each series of mattes, the higher the Ni/Cu ratio, the lower the sulphur content.

The curves drawn to fit the data points in Figures 1-4 represent, therefore, the average Ni/Cu ratios for all of the tests. In fact, the points on these figures are points on a family of curves with different Ni/Cu ratios. This is shown in Figure 10 for two different Ni/Cu ranges at 1100°C. Similar results were obtained at 1200°C . These results are presented in Figures 11 and 12.

The results of the tests obtained at 1100 and 1200°C are compared with published metal saturation boundary data for the Cu-Fe-S and the Ni-Fe-S ternary systems. These are presented in Figures 13 and 14. The data in Figure 13 (1100°C) shows the Ni-Fe-S and Cu-Fe-S systems obtained from Vogel and Tonn (4) and Reuleaux (8), respectively. The data in Figure 14 (1200°C) were obtained from Lenz et al. (6) and Reuleaux (8). The experimental values obtained using the Ni-Cu-Fe-S system fall close to the Cu-Fe-S saturation boundary. The alloy precipitated in the current study is nickel rich with a copper content varying between 1.4 to 7.4 mass percent. The average copper content of the alloy phase is in the order of 4%. The results plotted in Figures 13 and 14 have total S+O as one of the sides of the triangle. This has the effect of shifting the saturation boundary slightly towards the sulphur apex.

Tests at 1200°C indicate that for low grade mattes (Σ(Ni+Cu) = 22%;Ni/Cu= ~1.0), the alloy composition will approximate 21.5% Ni, 3.5% Cu and 75% Fe. For higher grade mattes at 1200°C (Σ (Ni+Cu) = 30), the alloy composition will approximate 30.5% Ni, 5% Cu and 64.5% Fe. Samples taken from electric furnace buildup have analysed, on average, 42.1% Ni+Co, 3.4% Cu and 54.3% Fe.

The liquidus curves obtained in this study are in excellent agreement with those obtained by Sobolev et al. (7) (with Ni:Cu=1). For example, results obtained by these investigators at 1100°C are superimposed on Figure 10. Similar agreement was obtained at other temperatures. It should be noted that in the present investigation one of the apices of the composition triangle is Σ (S+O). Sobolev et al. (7) do not measure the oxygen content of their samples and simply plot their results using % S.

The data obtained in this study are important from an industrial perspective. As previously explained, under the 'Environmental Improvement Program', the amount of sulphur elimination in the roasters has been increased to approximately 60%. This increase results in more heavily oxidized calcines and higher matte grades in the electric furnace. Both effects are detrimental to smelter metal recoveries. The counter-measure is to smelt under more intensive reducing conditions by raising the reductant feedrate. One limit to the coke additions is when the matte composition reaches the metal saturation boundary. In this study it was shown that the temperature of the system, as well as the Ni/Cu ratio of the matte affect the saturation boundary. A decrease in the temperature shifts the boundary towards the sulphur apex and to lower iron levels.

In the coke reduction zone, the appearance of a metallic phase fixes the thermodynamic conditions with respect to the oxygen potential of the system. This limit is critical to metal recovery as the nickel and cobalt losses to the slag are related to the oxygen potential. In the bulk matte zone, the precipitation of metallics can lead to a buildup of crusts on the furnace hearth because the metallic phase has a density that is higher than the matte's. It is desirable to maintain some frozen material on the hearth, however, excessive buildups reduce the capacity of the furnace and intefere with tapping of the furnace.

The amount of metallic iron in the furnace matte is affected by the addition of coke. The iron content is a measure of the reducing potential of the furnace. In general, the higher the iron level in the matte, the higher are the metal recoveries. The penalty for raising the metallic iron level is an increase in the melting point of the matte. This further aggravates the buildup problem on the hearth. The metallic iron in the matte also influences the operation of the converters since this iron provides substantial heat release during the converting operation.

Before the, 'Falconbridge Environmental Improvement Program' can be successfully implemented, the complex relationships concerning coke addition, metal precipitation, nickel recovery, and production costs must be investigated and fully understood.

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TABLE 1 - EXPERIMENTAL DATA

MATTE PHASE														ALLOY PHASE				
RAW DATA (MASS %)						NORMALIZED (MASS %)												
Ni-Matte	Cu-Matte	Fe-Matte	S-Matte	O-Matte	Sum-Matte	Norm-Ni	Norm-Cu	Norm-Fe	Norm-S	Norm-O	Ni+Cu	S+O	Ni/Cu	Ni-Met	Cu-Met	Fe-Met	T (°C)	TEST #
15.70	15.90	39.00	24.30	1.10	96.00	16.35	16.56	40.63	25.31	1.15	32.92	26.46	0.99	32.00	4.40	63.60	1100	1
12.40	11.50	46.00	24.40	1.70	96.00	12.92	11.98	47.92	25.42	1.77	24.90	27.19	1.08	23.20	2.80	73.00	1100	2
9.92	8.73	50.00	25.40	1.40	95.45	10.39	9.15	52.38	26.61	1.47	19.54	28.08	1.14	18.10	1.80	78.90	1100	3
22.00	18.20	33.00	21.60	1.20	96.00	22.92	18.96	34.38	22.50	1.25	41.88	23.75	1.21	41.90	6.50	51.90	1100	4
18.30	13.00	39.00	23.60	1.60	95.50	19.16	13.61	40.84	24.71	1.68	32.77	26.39	1.41	35.50	4.10	60.10	1100	5
14.50	9.74	47.00	22.90	1.40	95.54	15.18	10.19	49.19	23.97	1.47	25.37	25.43	1.49	25.40	2.60	71.10	1100	6
11.30	7.34	52.00	23.90	1.20	95.74	11.80	7.67	54.31	24.96	1.25	19.47	26.22	1.54	18.50	1.60	78.80	1100	7
24.00	16.10	33.00	21.70	1.10	95.90	25.03	16.79	34.41	22.63	1.15	41.81	23.77	1.49	45.30	5.70	49.40	1100	8
17.30	15.30	39.00	23.90	1.60	97.10	17.82	15.76	40.16	24.61	1.65	33.57	26.26	1.13	34.50	4.20	60.40	1100	9
9.80	8.80	48.00	27.20	1.50	95.30	10.28	9.23	50.37	28.54	1.57	19.52	30.12	1.11	19.70	1.40	76.20	1000	10
13.70	13.40	41.00	25.90	1.50	95.50	14.35	14.03	42.93	27.12	1.57	28.38	28.69	1.02	31.40	2.90	64.40	1000	11
17.60	16.10	36.00	25.20	1.20	96.10	18.31	16.75	37.46	26.22	1.25	35.07	27.47	1.09	40.90	4.20	55.70	1000	12
18.40	20.10	32.00	24.00	1.70	96.20	19.13	20.89	33.26	24.95	1.77	40.02	26.72	0.92	44.20	5.70	50.30	1000	13
10.80	7.80	49.00	26.80	1.60	96.00	11.25	8.13	51.04	27.92	1.67	19.38	29.58	1.38	21.30	1.40	77.00	1000	14
15.20	11.80	41.00	25.80	1.60	95.40	15.93	12.37	42.98	27.04	1.68	28.30	28.72	1.29	32.70	2.70	62.80	1000	15
19.30	14.00	37.00	25.00	1.40	96.70	19.96	14.48	38.26	25.85	1.45	34.44	27.30	1.38	41.50	4.00	54.80	1000	16
20.40	17.70	32.00	24.30	1.60	96.00	21.25	18.44	33.33	25.31	1.67	39.69	26.98	1.15	46.50	5.20	48.60	1000	17
10.90	7.30	51.00	22.70	2.20	94.10	11.58	7.76	54.20	24.12	2.34	19.34	26.46	1.49	17.00	2.20	79.70	1200	18
14.90	10.40	45.00	22.30	1.50	94.10	15.83	11.05	47.82	23.70	1.59	26.89	25.29	1.43	23.70	3.40	70.90	1200	19
18.40	13.70	40.00	21.10	2.00	95.20	19.33	14.39	42.02	22.16	2.10	33.72	24.26	1.34	31.30	5.00	62.50	1200	20
22.20	16.30	34.00	19.70	1.20	93.40	23.77	17.45	36.40	21.09	1.28	41.22	22.38	1.36	37.00	7.40	53.20	1200	21
11.70	6.40	51.00	23.00	1.50	93.60	12.50	6.84	54.49	24.57	1.60	19.34	26.18	1.83	17.10	2.00	80.40	1200	22
16.30	8.80	46.00	21.90	1.30	94.30	17.29	9.33	48.78	23.22	1.38	26.62	24.60	1.85	28.70	2.60	67.20	1200	23
21.00	11.70	40.00	20.70	1.70	95.10	22.08	12.30	42.06	21.77	1.79	34.38	23.55	1.79	33.60	4.50	61.30	1200	24
24.80	15.00	35.00	19.00	1.20	95.00	26.11	15.79	36.84	20.00	1.26	41.89	21.26	1.65	39.90	6.70	52.70	1200	25
15.80	16.30	41.30	24.70	0.88	98.98	15.96	16.47	41.73	24.95	0.89	32.43	25.84	0.97	30.80	3.96	65.20	1100	26
19.20	14.40	41.60	24.70	1.16	101.06	19.00	14.25	41.16	24.44	1.15	33.25	25.59	1.33	36.40	4.02	59.50	1100	27
14.00	11.60	48.20	26.30	0.93	101.03	13.86	11.48	47.71	26.03	0.92	25.34	26.95	1.21	26.30	2.55	71.00	1100	28
10.80	8.60	53.60	26.70	1.03	100.73	10.72	8.54	53.21	26.51	1.02	19.26	27.53	1.26	19.30	1.81	78.70	1100	29
18.80	15.00	42.20	24.50	0.81	101.31	18.56	14.81	41.65	24.18	0.80	33.36	24.98	1.25	31.60	3.96	64.30	1100	30
11.40	8.80	51.20	25.20	1.11	97.71	11.67	9.01	52.40	25.79	1.14	20.67	26.93	1.30	-	-	-	1200	31
22.60	19.90	35.20	22.40	0.68	100.78	22.43	19.75	34.93	22.23	0.67	42.17	22.90	1.14	39.70	6.82	53.30	1200	32
19.80	15.70	40.00	23.60	0.80	99.90	19.82	15.72	40.04	23.62	0.80	35.54	24.42	1.26	-	-	-	1200	33
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1300	34
23.50	19.60	33.60	21.70	1.10	99.50	23.62	19.70	33.77	21.81	1.11	43.32	22.91	1.20	49.60	5.75	44.50	1300	35
15.50	13.00	45.20	24.20	0.00	97.90	15.83	13.28	46.17	24.72	0.00	29.11	24.72	1.19	32.10	3.43	64.40	1300	36
10.70	10.00	53.00	25.90	0.89	100.49	10.65	9.95	52.74	25.77	0.89	20.60	26.66	1.07	21.30	1.94	76.60	1200	37
24.20	19.50	34.00	21.90	1.02	100.62	24.05	19.38	33.79	21.77	1.01	43.43	22.78	1.24	43.30	7.06	49.60	1200	38
15.30	13.60	45.80	25.30	1.00	101.00	15.15	13.47	45.35	25.05	0.99	28.61	26.04	1.13	29.00	3.09	67.80	1200	39
10.30	9.60	51.50	26.30	1.38	99.08	10.40	9.69	51.98	26.54	1.39	20.08	27.94	1.07	19.00	1.95	78.90	1100	40
21.00	20.80	34.30	23.40	1.29	100.79	20.84	20.64	34.03	23.22	1.28	41.47	24.50	1.01	41.20	5.90	52.80	1100	41
18.30	16.00	39.80	24.30	1.38	99.78	18.34	16.04	39.89	24.35	1.38	34.38	25.74	1.14	36.30	3.91	59.60	1100	42
11.50	10.80	51.50	22.60	1.22	97.62	11.78	11.06	52.76	23.15	1.25	22.84	24.40	1.06	17.80	2.78	79.30	1300	43
13.50	11.80	50.50	21.50	1.23	98.53	13.70	11.98	51.25	21.82	1.25	25.68	23.07	1.14	24.90	5.24	64.30	1300	44
16.30	13.00	46.50	21.30	1.14	98.24	16.59	13.23	47.33	21.68	1.16	29.82	22.84	1.25	32.30	3.51	64.10	1300	45
19.30	15.50	45.30	17.60	1.17	98.87	19.52	15.68	45.82	17.80	1.18	35.20	18.98	1.25	-	-	-	1300	46
22.50	17.30	39.00	18.80	0.94	98.54	22.83	17.56	39.58	19.08	0.95	40.39	20.03	1.30	-	-	-	1300	47
9.80	10.40	58.80	22.60	1.15	102.75	9.54	10.12	57.23	22.00	1.12	19.66	23.11	0.94	14.80	2.50	82.60	1200	48
12.00	13.80	50.60	23.50	1.01	100.91	11.89	13.68	50.14	23.29	1.00	25.57	24.29	0.87	22.50	3.63	73.90	1200	49
19.00	17.60	41.60	22.10	0.95	101.25	18.77	17.38	41.09	21.83	0.94	36.15	22.77	1.08	33.90	5.14	60.90	1200	50
16.20	16.40	46.00	20.10	1.38	100.08	16.19	16.39	45.96	20.08	1.38	32.57	21.46	0.99	51.10	3.64	45.20	1000	51
21.60	22.00	32.00	23.80	0.98	100.38	21.52	21.92	31.88	23.71	0.98	43.43	24.69	0.98	47.50	5.46	47.00	1000	52
10.60	14.00	49.60	24.90	1.23	100.33	10.57	13.95	49.44	24.82	1.23	24.52	26.04	0.76	23.50	2.63	73.80	1000	53

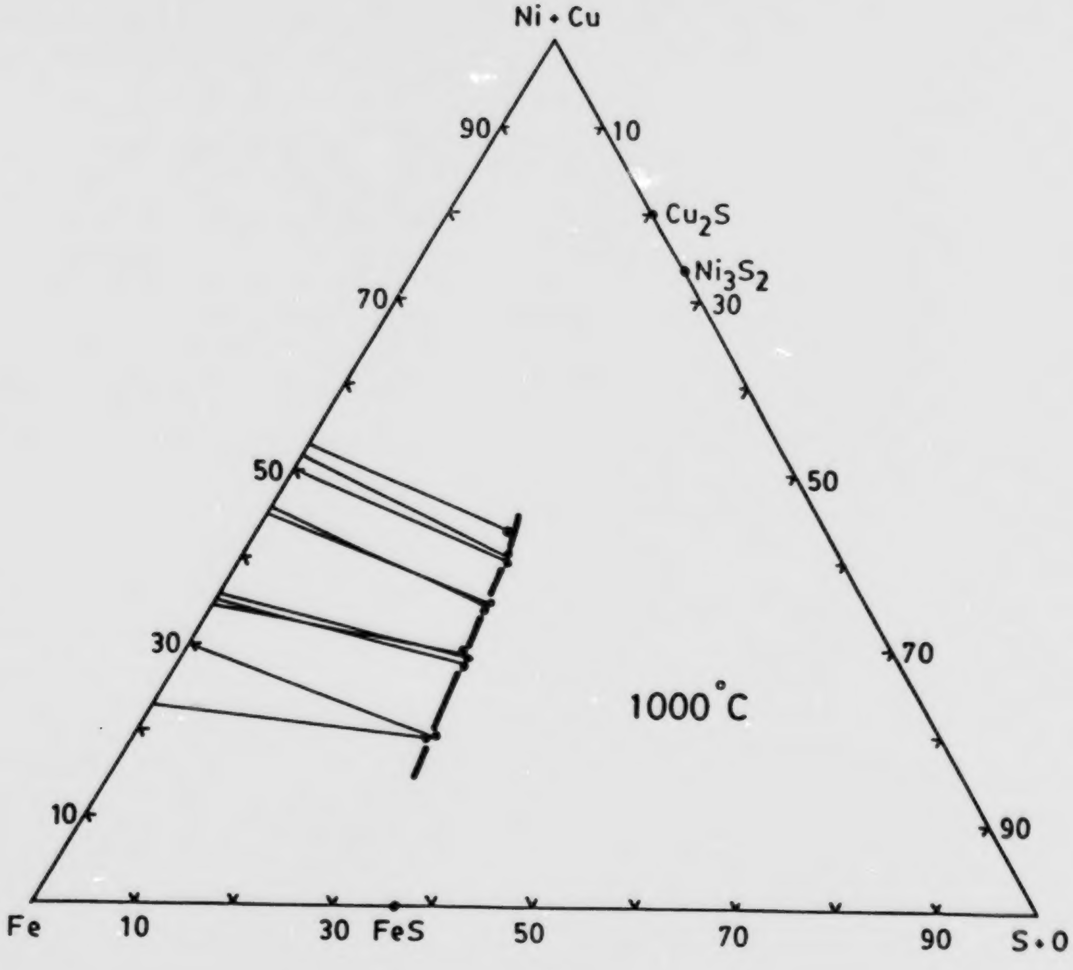


FIGURE 1 - TIE-LINES IN THE LIQUID & ALLOY REGION FOR THE (Ni+Cu)-Fe-S SYSTEM AT 1000°C

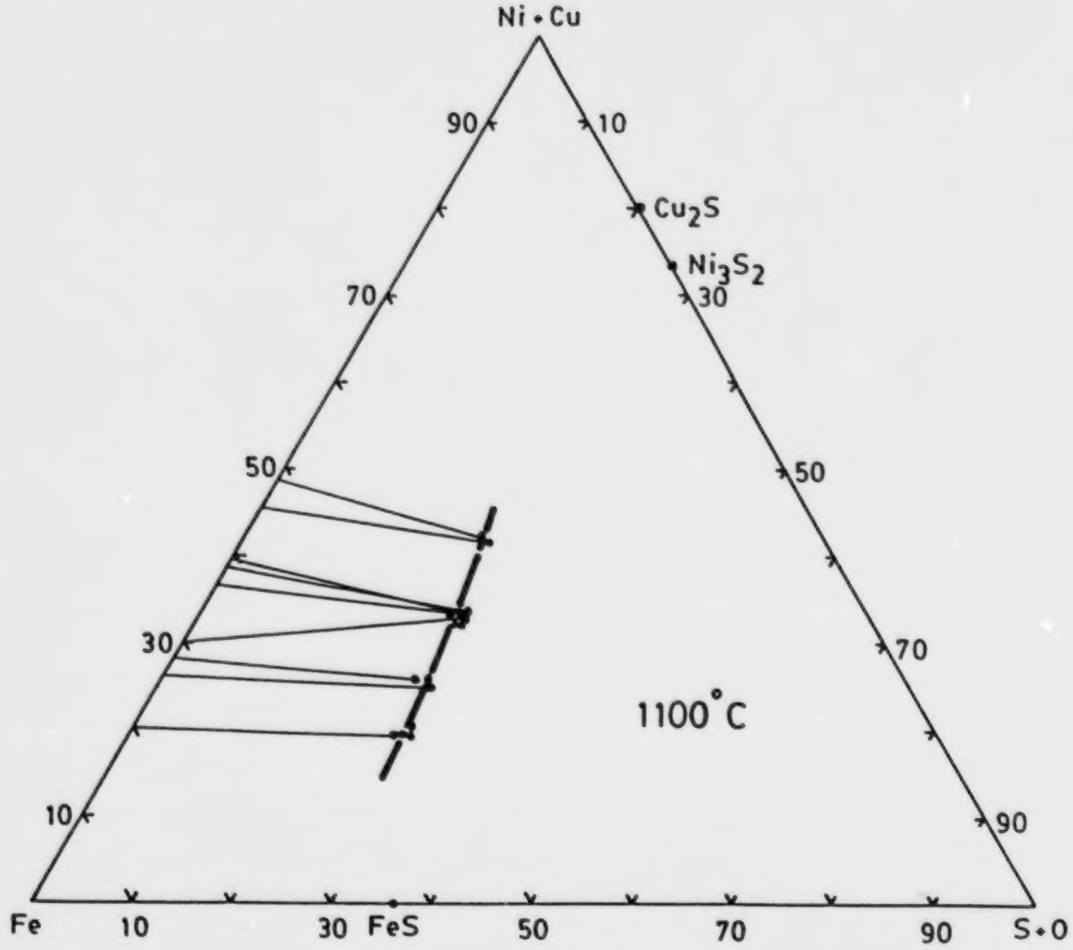


FIGURE 2 - TIE-LINES IN THE LIQUID & ALLOY REGION FOR THE (Ni+Cu)-Fe-S SYSTEM AT 1100°C

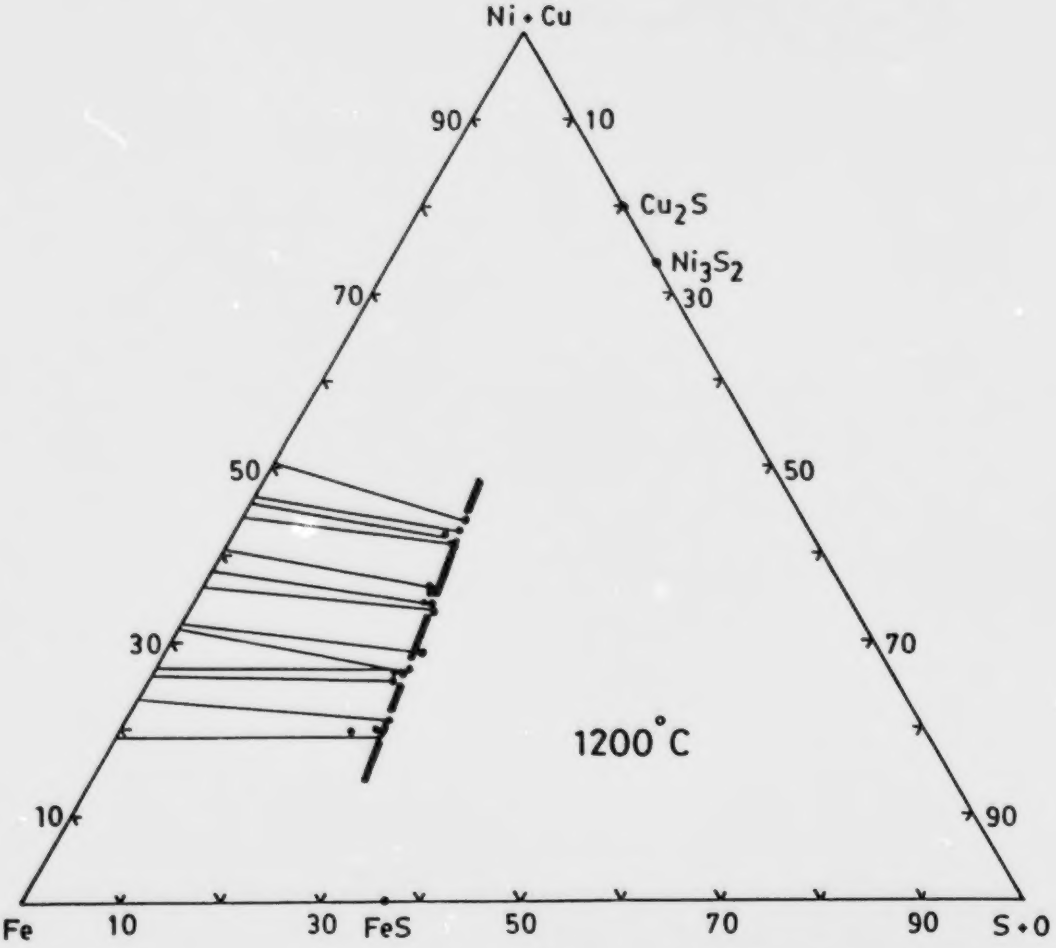


FIGURE 3 - TIE-LINES IN THE LIQUID & ALLOY REGION FOR THE (Ni+Cu)-Fe-S SYSTEM AT 1200°C

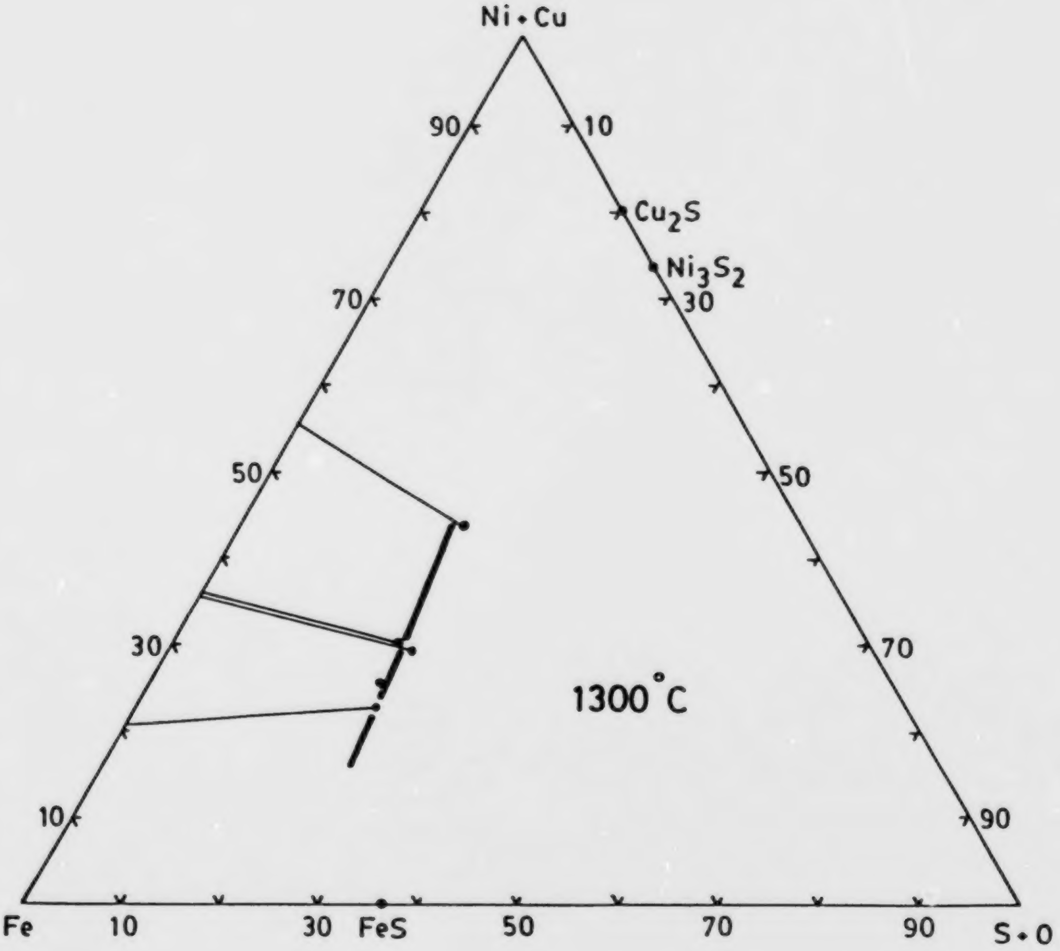


FIGURE 4 - TIE-LINES IN THE LIQUID & ALLOY REGION FOR THE (Ni+Cu)-Fe-S SYSTEM AT 1300°C

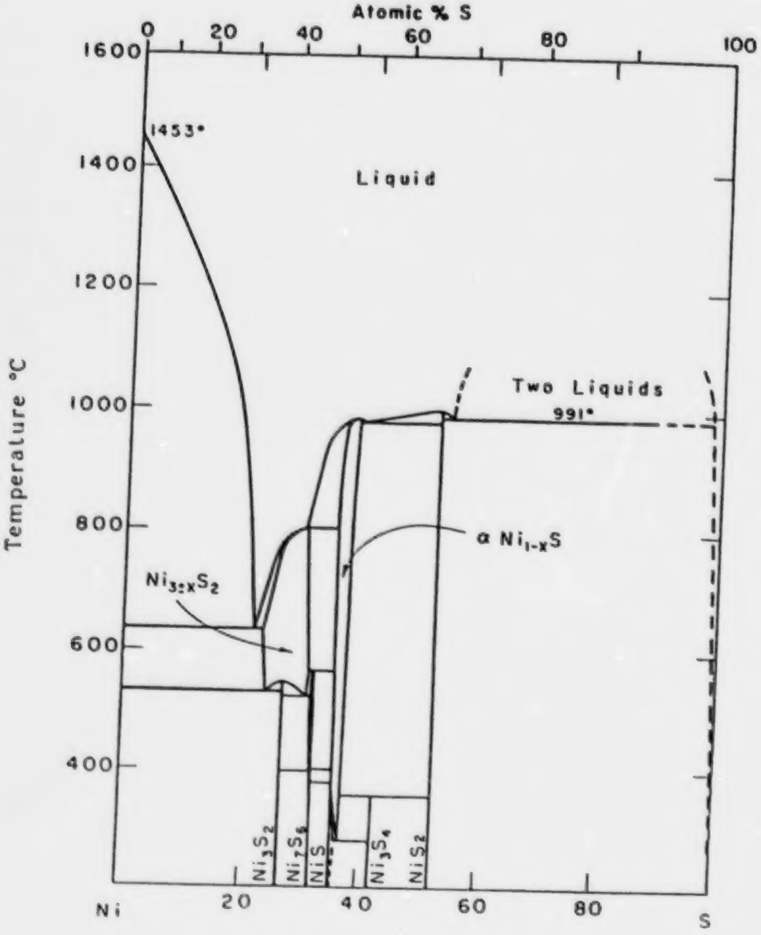


FIGURE 5 - THE Ni-S PHASE DIAGRAM$^{(1)}$

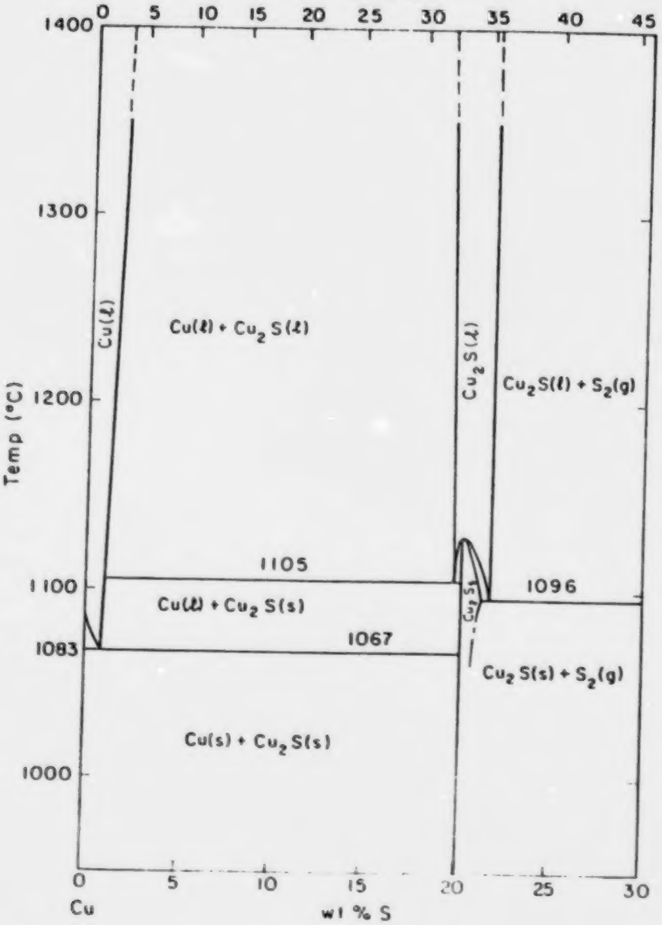


FIGURE 6 - THE Cu-S PHASE DIAGRAM(2)

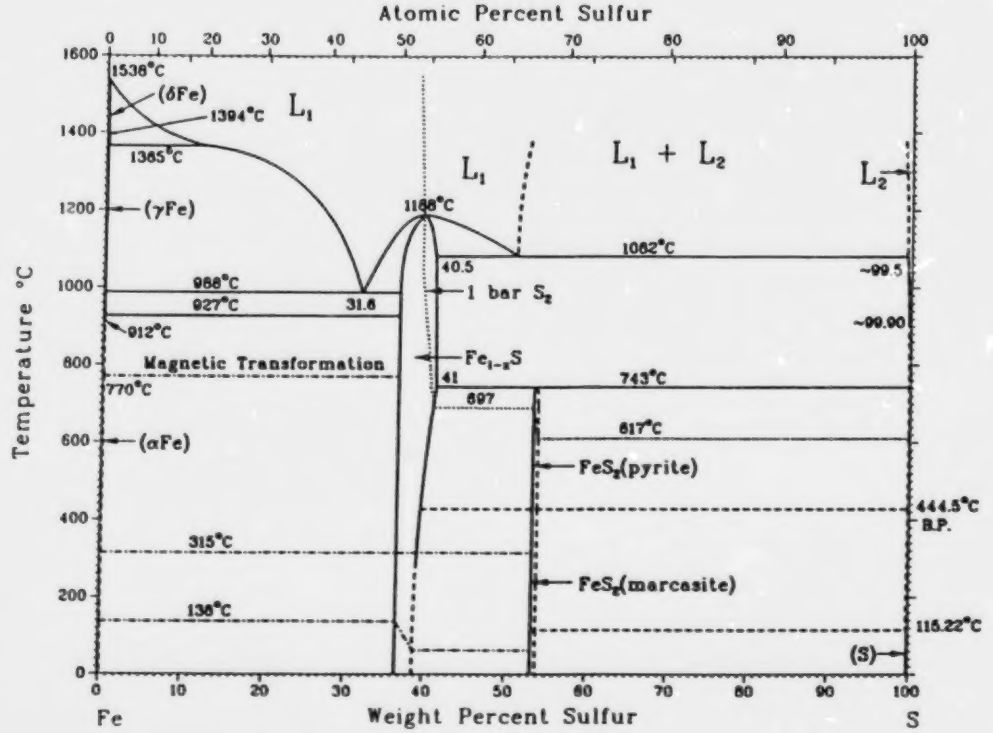


FIGURE 7 - THE Fe-S PHASE DIAGRAM(3)

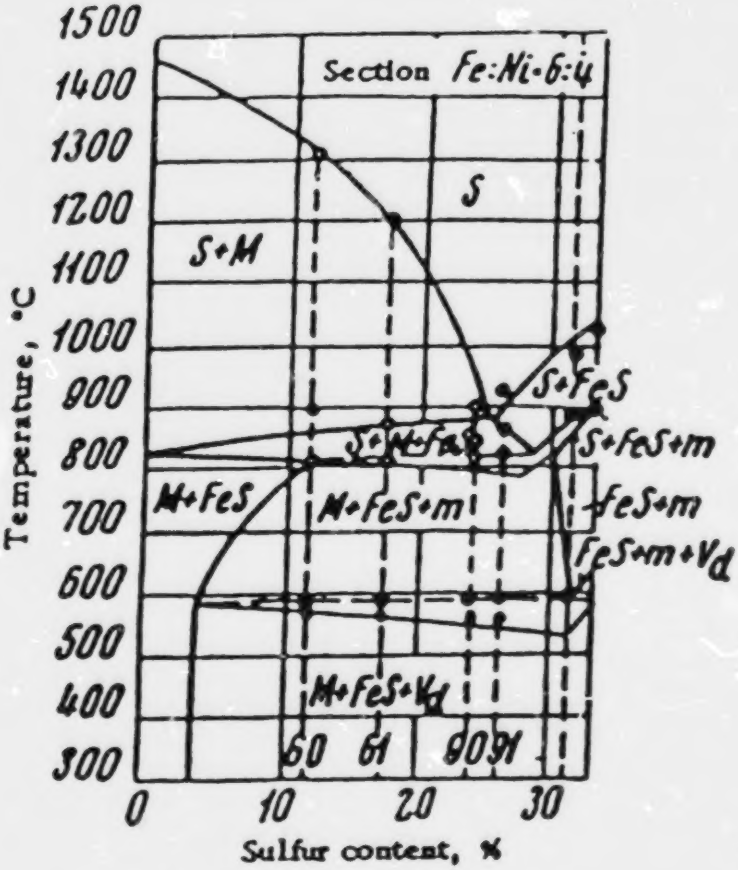


FIGURE 8 - A SECTION OF THE Ni-Fe-S PHASE DIAGRAM (4)

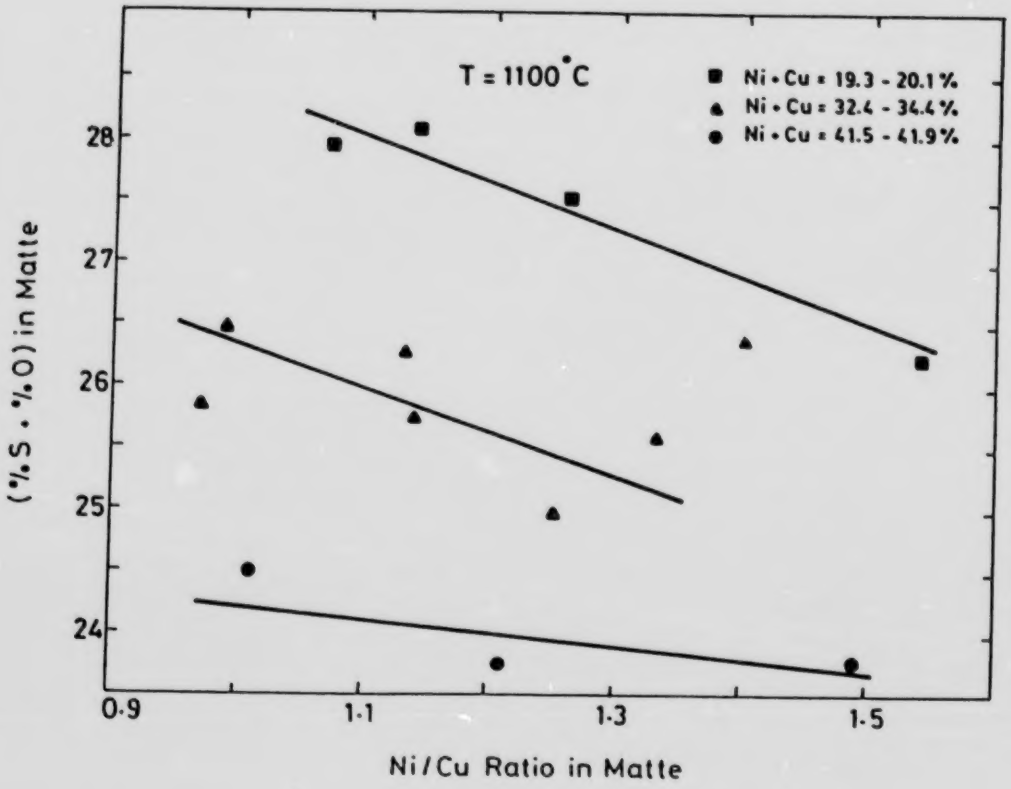


FIGURE 9 - SULPHUR AND OXYGEN CONTENT OF MATTE AS A FUNCTION OF Ni/Cu RATIO

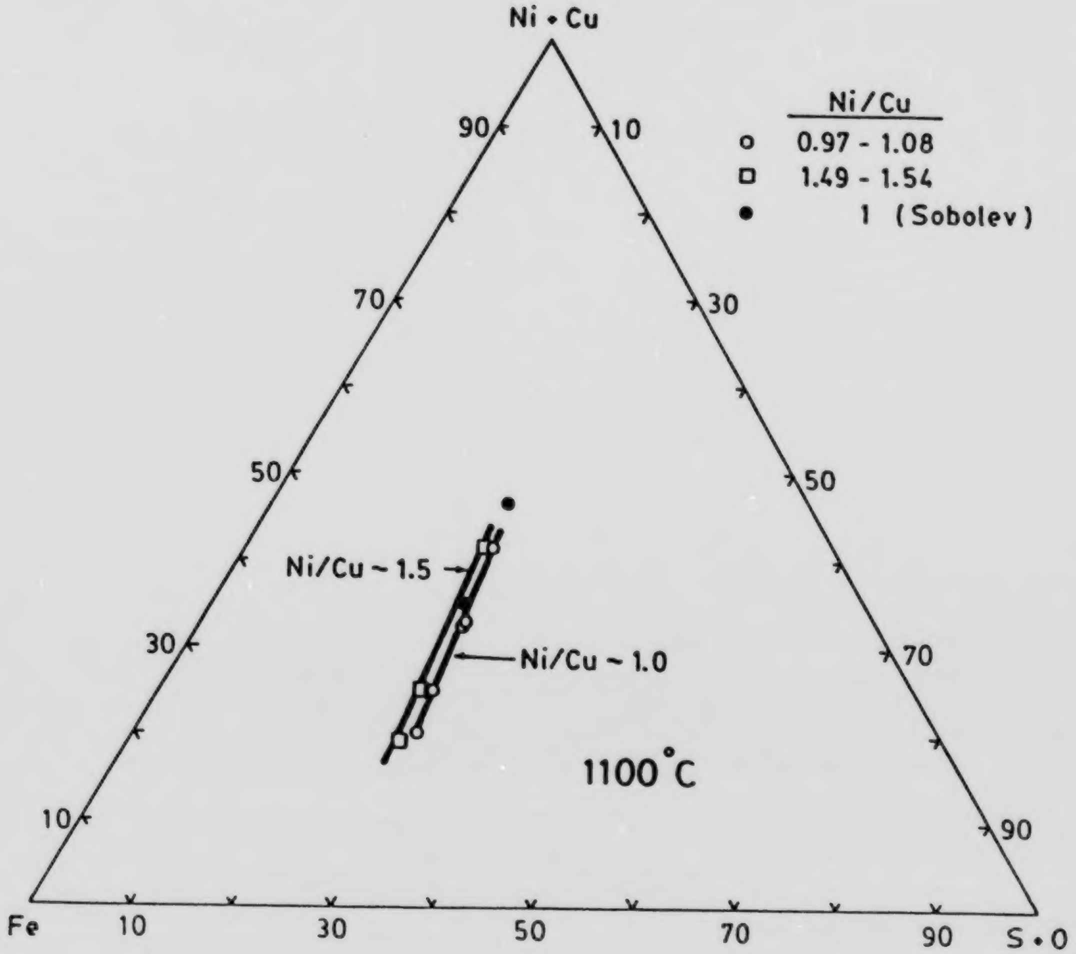


FIGURE 10 - THE EFFECT OF THE Ni/Cu RATIO ON THE MATTE-METAL SATURATION BOUNDARY

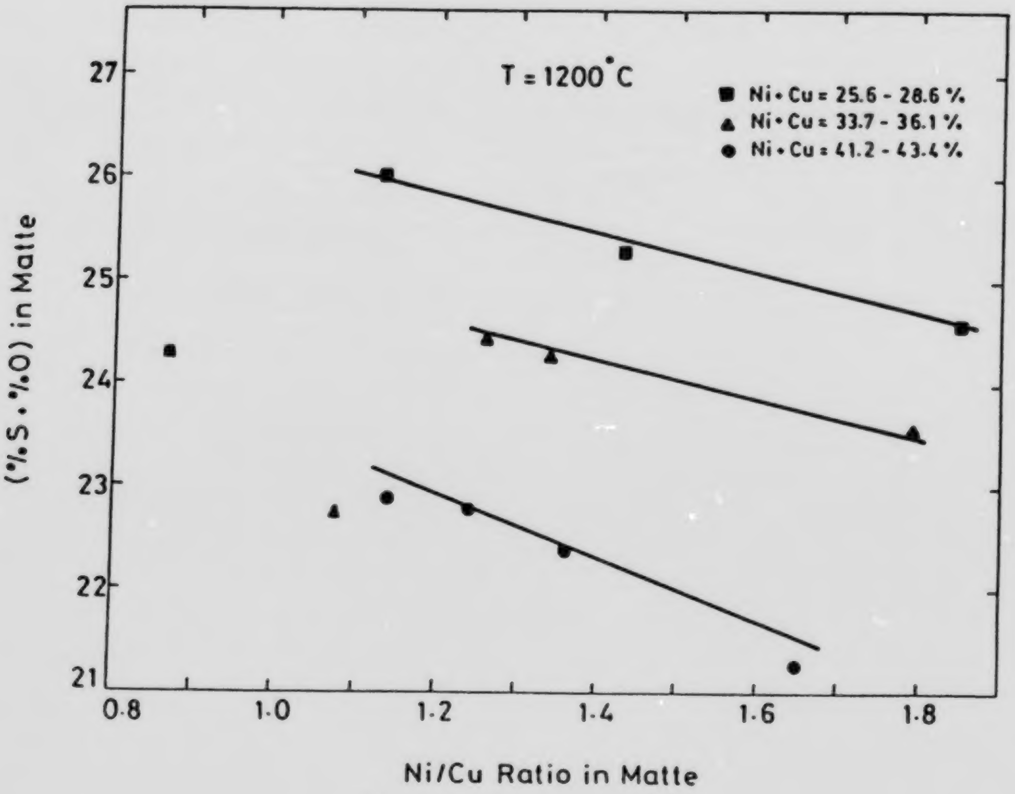


FIGURE 11 - SULPHUR AND OXYGEN CONTENT OF MATTE AS A FUNCTION OF Ni/Cu RATIO (1200°C)

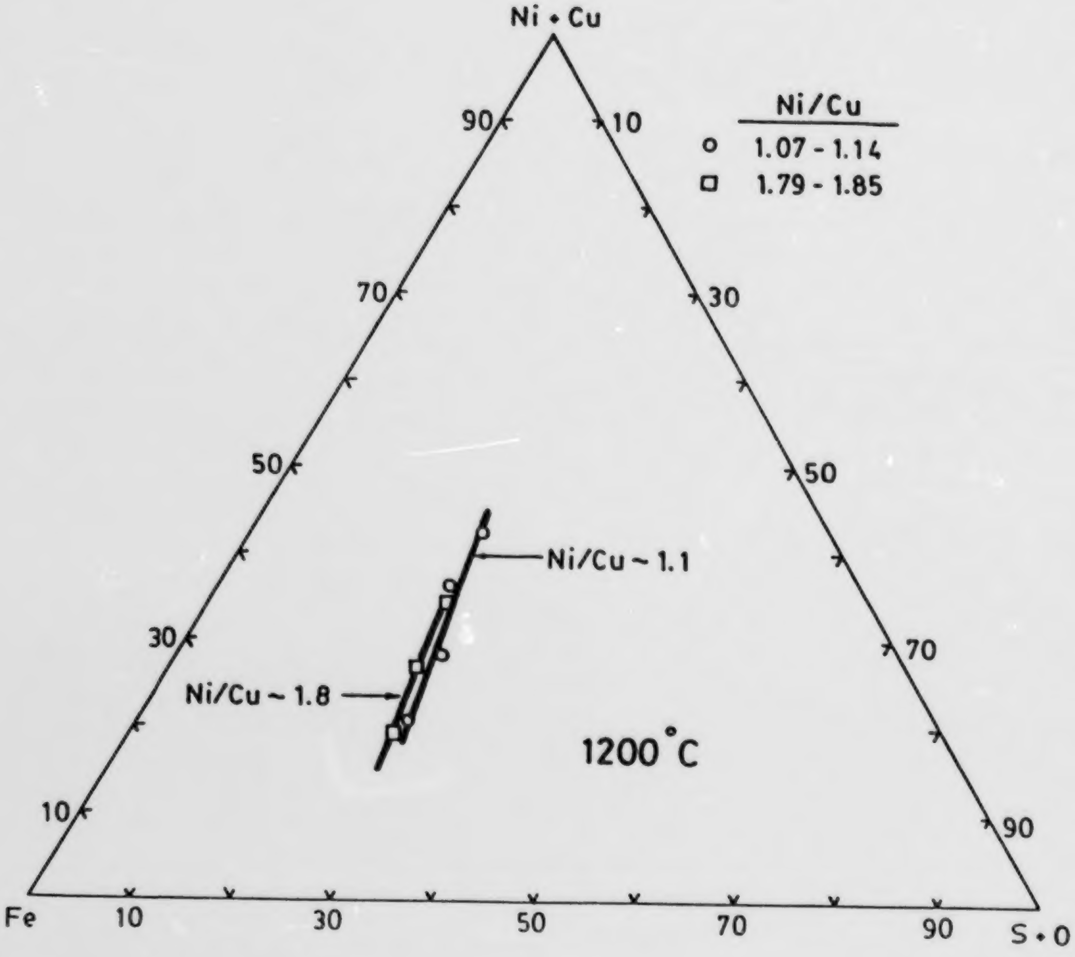


FIGURE 12 - THE EFFECT OF THE Ni/Cu RATIO ON THE MATTE-METAL SATURATION BOUNDARY

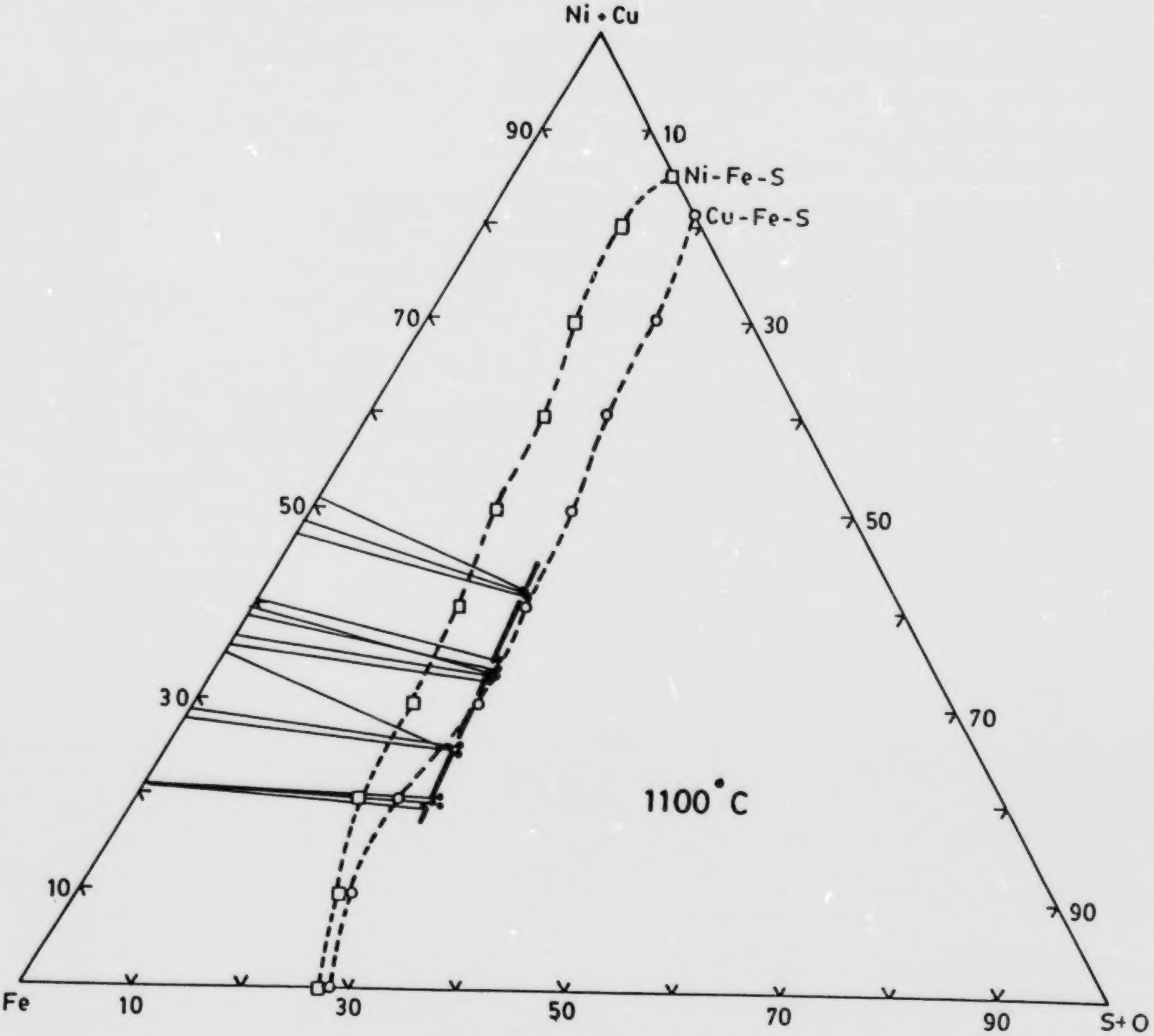


FIGURE 13 - COMPARISON OF RESULTS OBTAINED IN THE PRESENT INVESTIGATION WITH THE Ni-Fe-S and Cu-Fe-S SYSTEMS

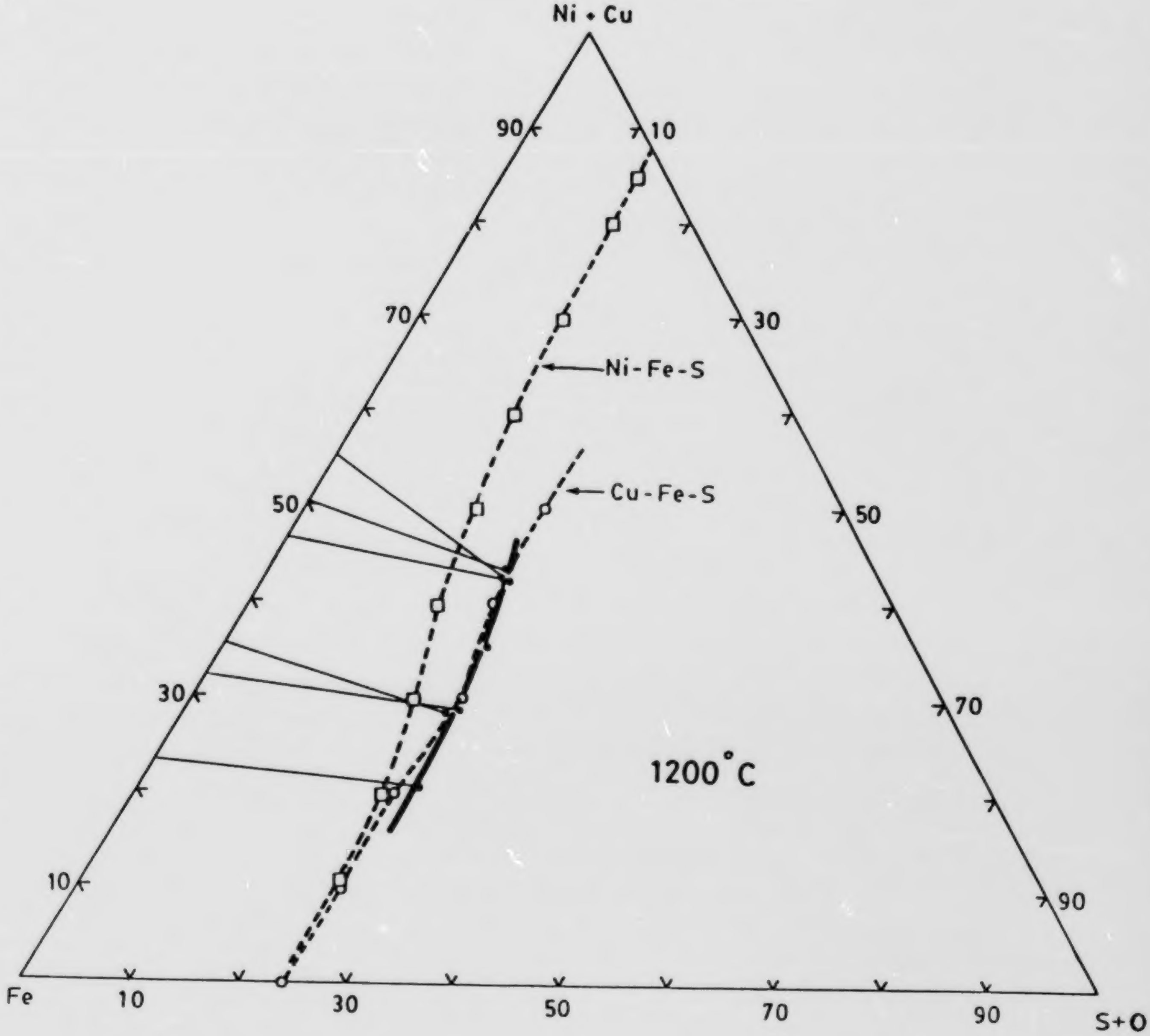
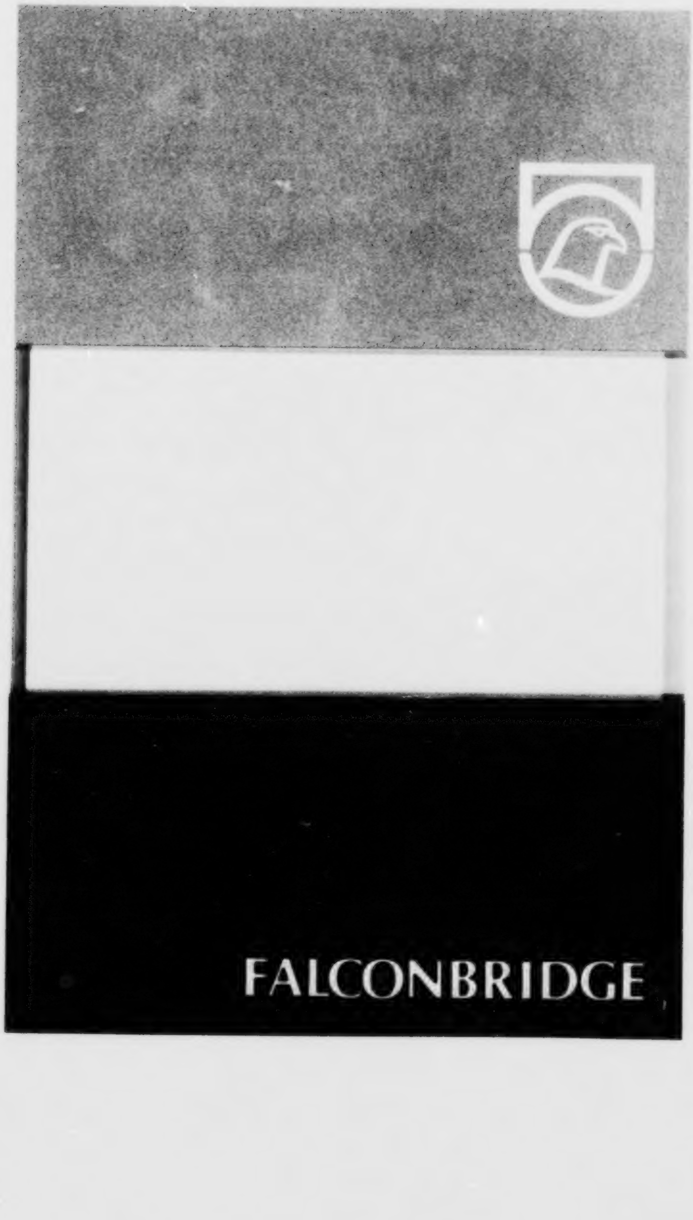


FIGURE 14 - COMPARISON OF RESULTS OBTAINED IN THE PRESENT INVESTIGATION WITH THE Ni-Fe-S and Cu-Fe-S SYSTEMS (1200°C)

Volume

4



FALCONBRIDGE

TO DEVELOP A CLEAN SMELTING PROCESS FOR HIGHLY ROASTED COPPER-NICKEL CALCINES AND TO IMPROVE METAL RECOVERY

PART D:

ELECTRICAL CONDUCTIVITY MEASUREMENTS OF ELECTRIC FURNACE SMELTING SLAGS

by

N. M. Stubina and G. H. Kaiura (Falconbridge Limited)
H. Tseng and J. M. Toguri (University of Toronto)

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MICROMEDIA

EXECUTIVE SUMMARY

A laboratory-scale study was initiated in order to yield electrical conductivity data for electric furnace smelting slags. A molybdenum crucible-probe conductivity cell was used for the determinations. Some of the parameters investigated include: temperature, Fe/SiO_2 ratio, lime content, and Fe_2O_3 additions to the slag. Electrical conductivity data are necessary in order to predict the behaviour of electric furnaces as the slag chemistry is altered.

SOMMAIRE

Une étude en laboratoire a été effectuée afin de déterminer les données de la conductivité électrique des scories de fusion dans les fours électriques. Une cellule conductive en forme de creuset-sonde fabriquée de molybdène a été utilisée pour obtenir ces données. Parmis les paramètres étudiés on compte les suivants: le rapport de Fe/SiO_2, la quantité de chaux et les additions de Fe_2O_3 à la scorie. Les données de conductivité électrique son nécessaire afin de prédir le fonctionnement des fours électriques à mesure que change la composition chimique de la scorie.

TABLE OF CONTENTS

	PAGE
EXECUTIVE SUMMARY	
SOMMAIRE	
INTRODUCTION	1
EXPERIMENTAL	1
Apparatus	1
Procedure	5
EXPERIMENTAL RESULTS AND DISCUSSION	6
SUMMARY	11
REFERENCES	13

APPENDIX I: Data For Electrical Conductivity Measurements

APPENDIX II: Calculated Electrical Conductivity Values for all Samples

INTRODUCTION

In order to meet environmental requirements and to cut operating costs, a new smelting process was commissioned for Falconbridge Limited's Sudbury operation in 1978. The current process consists of two fluid bed roasters, two electric furnaces, a converter aisle, and an acid plant. The new operation was designed to remove 50% of the sulphur entering the roasters. In order to reduce SO_2 emissions even further, the smelter has recently increased the degree of roast to 60%. This allows more of the sulphur entering the fluid bed roaster to be fixed as sulphuric acid.

Changes that are made to the roasting operation also affect the operation of the electric furnaces. In this work, the electrical conductivity of smelting slags was examined as a function of temperature, Fe/SiO_2 ratio, lime content, and Fe_2O_3 additions to the slag. Industrially, electrical conductivity data are necessary to predict electric furnace behaviour as the slag chemistry is altered.

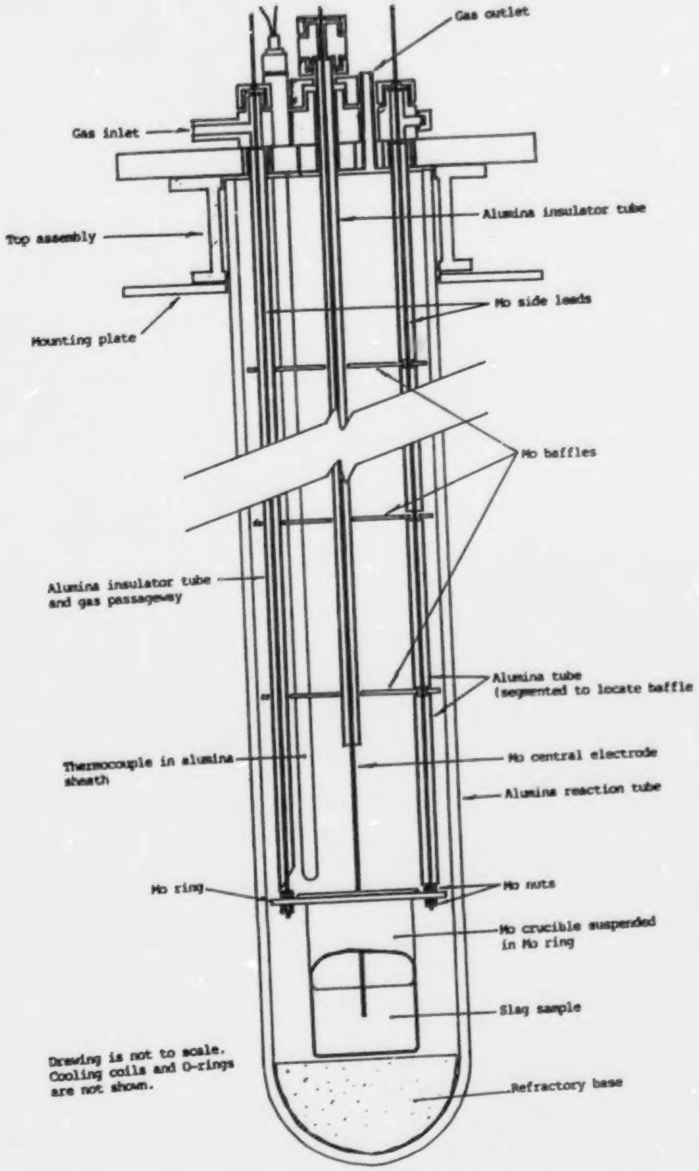
EXPERIMENTAL

Apparatus

The conductivity experiments were performed using an electrode-crucible conductivity cell. A schematic representation of the experimental apparatus is shown in Figure 1. The slag samples were contained in a cylindrically shaped molybdenum crucible (3.81 cm in diameter, 6.5 cm high). The crucible has a lip around its top and it is held in a ring made from molybdenum plate. The ring is suspended by two molybdenum rods from the top of the assembly. These rods serve as electrical contacts for the crucible and are enclosed in alumina tubes.

The crucible serves as one electrode, and a separate molybdenum rod (3 mm diameter) is placed coaxially to the crucible and serves as the central electrode. An alumina tube surrounds the central electrode in order to insulate it from the rest of the assembly. The central electrode is introduced into the cell through the top plate assembly. This arrangement is illustrated in Figure 2. The threaded screw on the elevating mechanism is connected to a digital counter which allows the vertical motion of the electrode to be precisely monitored. One unit on the counter corresponds to 0.127 mm of travel. The temperature of the cell was monitored by a type-R thermocouple located just above the crucible. The top plate is used to mount the various fittings for the central electrode, side leads, gas inlet and outlet, and thermocouple. Rubber O-rings are used to provide gas tight seals for all of the fittings.

A high-temperature tube furnace, heated by molybdenum windings, was used to melt the slag samples. The entire conductivity cell assembly is mounted on a metal frame which can be hydraulically moved, allowing the cell to be moved into or out of the furnace. A simplified view of this arrangement is shown in Figure 3.


Gas outlet
Gas inlet
Alumina insulator tube
Top assembly
Mo side leads
Mounting plate
Mo baffles
Alumina insulator tube and gas passageway
Alumina tube (segmented to locate baffle
Thermocouple in alumina sheath
Mo central electrode
Alumina reaction tube
Mo ring
Mo nuts
Mo crucible suspended in Mo ring
Slag sample
Refractory base

Drawing is not to scale. Cooling coils and O-rings are not shown.

Figure 1: Detail of Conductivity Cell Assembly

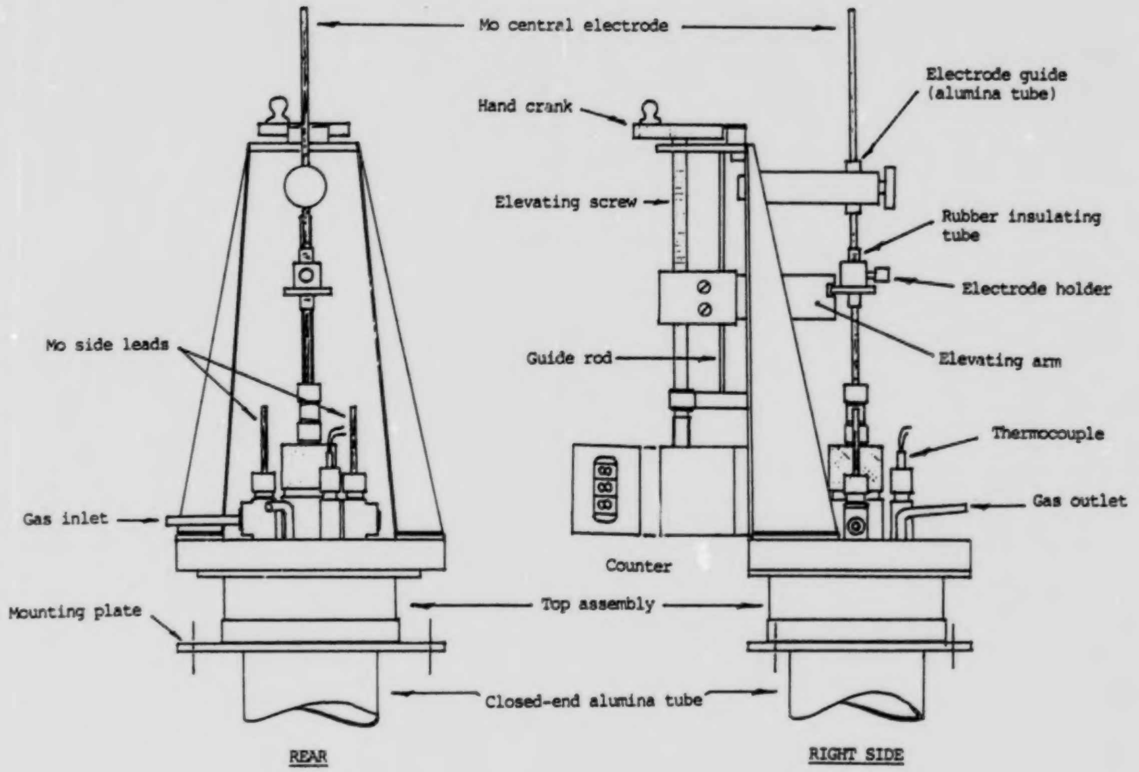

Mo central electrode
Hand crank
Electrode guide (alumina tube)
Elevating screw
Rubber insulating tube
Electrode holder
Mo side leads
Guide rod
Elevating arm
Thermocouple
Gas inlet
Gas outlet
Counter
Mounting plate
Top assembly
Closed-end alumina tube
REAR
RIGHT SIDE

Figure 2: Top Assembly Detail. Cooling Coils Have Been Omitted for Clarity.

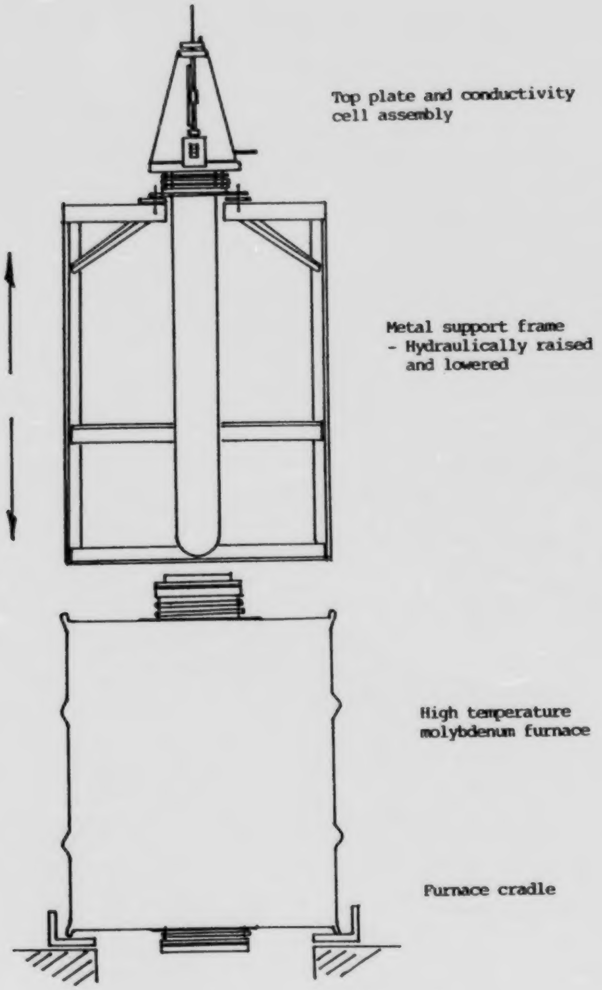

Top plate and conductivity cell assembly
Metal support frame
- Hydraulically raised and lowered
High temperature molybdenum furnace
Furnace cradle

Figure 3: Simplified View of Apparatus Set-Up.

Procedure

The electric furnace slag sample used in this study was obtained from Falconbridge Limited. The analysis of this slag is given in Table 1.

Table 1 (mass %)

S	-	1.08	MgO	-	2.37
Ni	-	0.093	CaO	-	2.35
Cu	-	0.188	Al_2O_3	-	6.20
Co	-	0.087	Fe_3O_4	-	3.00
Fe (total)	-	35.80	SiO_2	-	37.55

The Fe/SiO_2 ratio of the 'as-received' slag is 0.95. This ratio was decreased by adding silica and increased by the addition of FeO (using mixtures of hematite and iron powder). The additions were dried, and then intimately mixed with the 'as-received' slag before being loaded into the conductivity cell.

A sample mass of approximately 100 g was used in all conductivity experiments. This produced a melt depth of approximately 3.0 cm. The samples were not pre-melted (i.e. all melting took place during the actual experiments).

The slag sample was placed in a Mo crucible which was then loaded into the conductivity cell. A closed-end alumina tube was placed over the assembly and sealed to the top plate. The entire assembly was mounted onto the support frame and the water cooling and gas tubes were connected. The atmosphere inside of the cell was flushed with gettered high-purity argon gas. Next, the closed-end alumina tube was slowly lowered into the furnace by hydraulically lowering the support frame. Since the furnace was always kept at a relatively high temperature (>850°C), it was necessary to lower the tube extremely slowly to prevent it from cracking. The lowering operation normally took between two and three hours. Once the conductivity cell was completely in the furnace hot-zone, the furnace temperature was increased to the desired level. The samples were allowed to stabilize at the desired temperature for at least one hour before mesurements were taken. All experiments were performed at either 1250 or 1300°C.

A Hewlett Packard model 4328A milliohmeter was used for the resistance measurements. This device provides a 1 kc/s alternating current to prevent polarization at the electrodes. Due to the nature of the experimental apparatus, it was necessary to shut off all power to the furnace in order to obtain reliable resistance readings. With the power off, the central electrode was lowered until the surface of the melt was electrically identified (i.e. when the meter registered contact with the surface). Resistance measurements were taken at predetermined levels in the slag, stopping to reheat the sample whenever the cell temperature started to cool significantly. Measurements were taken until the bottom of the crucible was contacted. The contact resistance was noted as was the depth of the sample.

Measurements were only taken with the electrode lowered into the melt. When the electrode was raised, it tended to pull some slag with it. This resulted in erroneous measurements, especially near the surface of the melt.

Measurements were repeated three times at each of the two temperatures. After the experiment, the furnace temperature was lowered to its usual holding temperature and the cell was slowly raised out of the furnace. When the cell had cooled, the crucible containing the slag sample was removed and its change in mass was recorded. The sample was then sent to Falconbridge for chemical analysis.

EXPERIMENTAL RESULTS AND DISCUSSION

The conductivity of a melt can be calculated using the following equation:

$$\text{Specific Electrical Conductance} = \frac{K}{R-r} \qquad (1)$$

where:

K = the cell constant at a given electrode immersion level (cm^{-1})

R = the total resistance measured at the same level (ohm)

r = the external resistance of the system, including electrodes, contacts and leads (ohm).

The cell constant of the experimental apparatus was determined using a 1 N KCl solution at room temperature. A plot of the cell constant versus depth is shown in Figure 4.

The resistance measurements for each of the slag samples during the various experimental runs are tabulated in Appendix I. Ideally, for a given sample at a given temperature, the conductivities calculated from the measured resistance values at the various depths should be equal. From the results, however, there appears to be some variation of conductivity with depth. In most of the runs, the calculated conductivity values seem significantly lower towards the top of the melt. This can be attributed to a temperature gradient that exists within the sample. After extensive temperature profile tests, it was discovered that the temperature profile of the furnace was less than ideal. The use of a

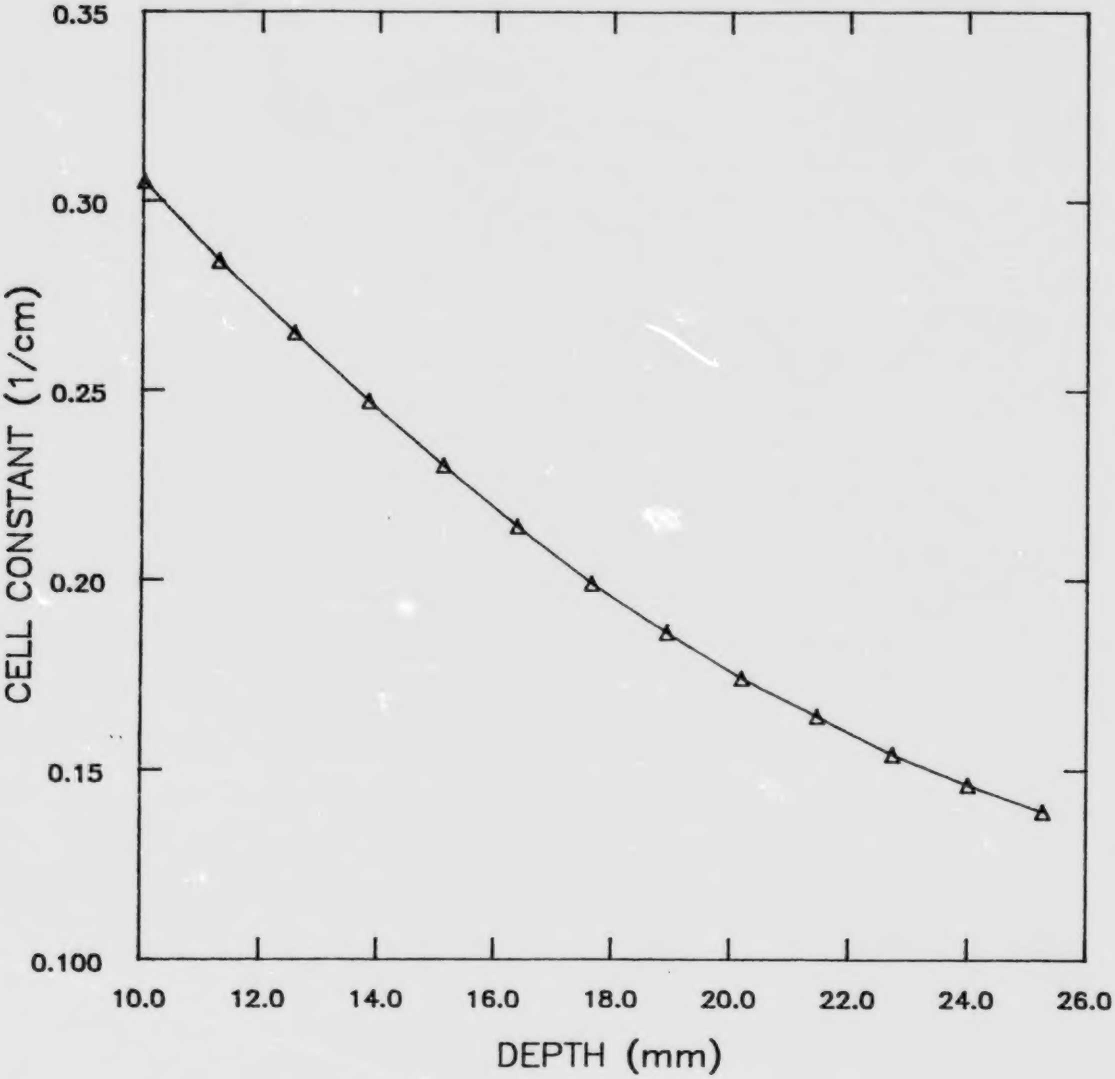


Figure 4: Cell Constant Calibration Curve

molybdenum lid over the crucible decreased the vertical temperature gradient to an acceptable level. The temperature indicated by the monitoring thermocouple in the conductivity cell was found to be lower than the actual temperature within the crucible. Tests were performed to determine the indicated temperature that corresponded to the desired temperature within the melt. The desired temperature was located near the middle of the slag sample.

The mean and standard deviation of the calculated conductivity values were determined. Two approaches were employed. In the first one, a 'wide' range of data (i.e. all calculated points excluding the two extremes) were considered for the statistical analysis. In the second case, a 'narrow' range (i.e. points withing a 5 mm range around the level of the desired temperature) were considered.

Values determined from the 'narrow' range population should be considered to be more accurate than those from the 'wide' range. The mean and standard deviation values for each run are tabulated in Appendix II. It is interesting to note that there seems to be more deviation for samples containing high levels of iron.

Every attempt was made to ensure that conditions were consistent for duplicate runs. Errors in indentifying the surface of the slag, reading the meter, and slight differences in temperature may account for some of the variations in the calculated conductivity values. With the monitoring thermocouple located outside of the crucible, and due to differences in heating and cooling rates inside and outside of the melt, the actual melt temperature could not be accurately determined when the power was switched on and off in order to take resistance readings. The temperature within the cell usually remained stable for a long enough time to complete the resistance measurements while the power was off. In reheating the melt for subsequent runs, however, it is possible that some resistance measurements were taken before the temperature was at the desired level. Wherever possible, any irregularities in the runs were identified and considered when comparing data between various runs. Runs that varied significantly from the others were disregarded.

After the conductivity experiments were completed, the slags were shipped to Falconbridge and analyzed for Fe (total), SiO_2, and CaO. The results are summarized in Table 2.

The effects of temperature, Fe/SiO_2 ratio, and oxygen content on the electrical conductivity of the slag are shown in Figure 5. A linear relationship was assumed for each of the test conditions due to the limited number of data points available. From these results, it is apparent that increases in temperature, Fe content, or oxygen content all increase the electrical conductivity of the slag. It should be noted that the addition of hematite to increase the oxygen content of the slag also increased the iron content, resulting in the lines for these additions to be shifted to the right. The values used in Figure 5 are indicted by asterisks in Appendix II.

TABLE 2 ANALYSIS OF SLAG SAMPLES

SLAG SAMPLE (TARGET)	Fe/SiO_2 *	CaO (mass %) *
0.85 Fe/SiO_2	0.843	2.04
0.85 Fe/SiO_2 + 5% Fe_2O_3	0.937	2.01
0.95 Fe/SiO_2	0.940	2.22
0.95 Fe/SiO_2 +5% Fe_2O_3	1.029	2.12
1.029 Fe/SiO_2	1.015	2.20
1.029 Fe/SiO_2 +5% Fe_2O_3	1.099	2.12
0.85 Fe/SiO_2 +7% CaO	0.838	6.00
0.85 Fe/SiO_2 +10% CaO	0.843	8.30
0.85 Fe/SiO_2 +15% CaO	0.845	10.70

*Based on Chemical Analyses

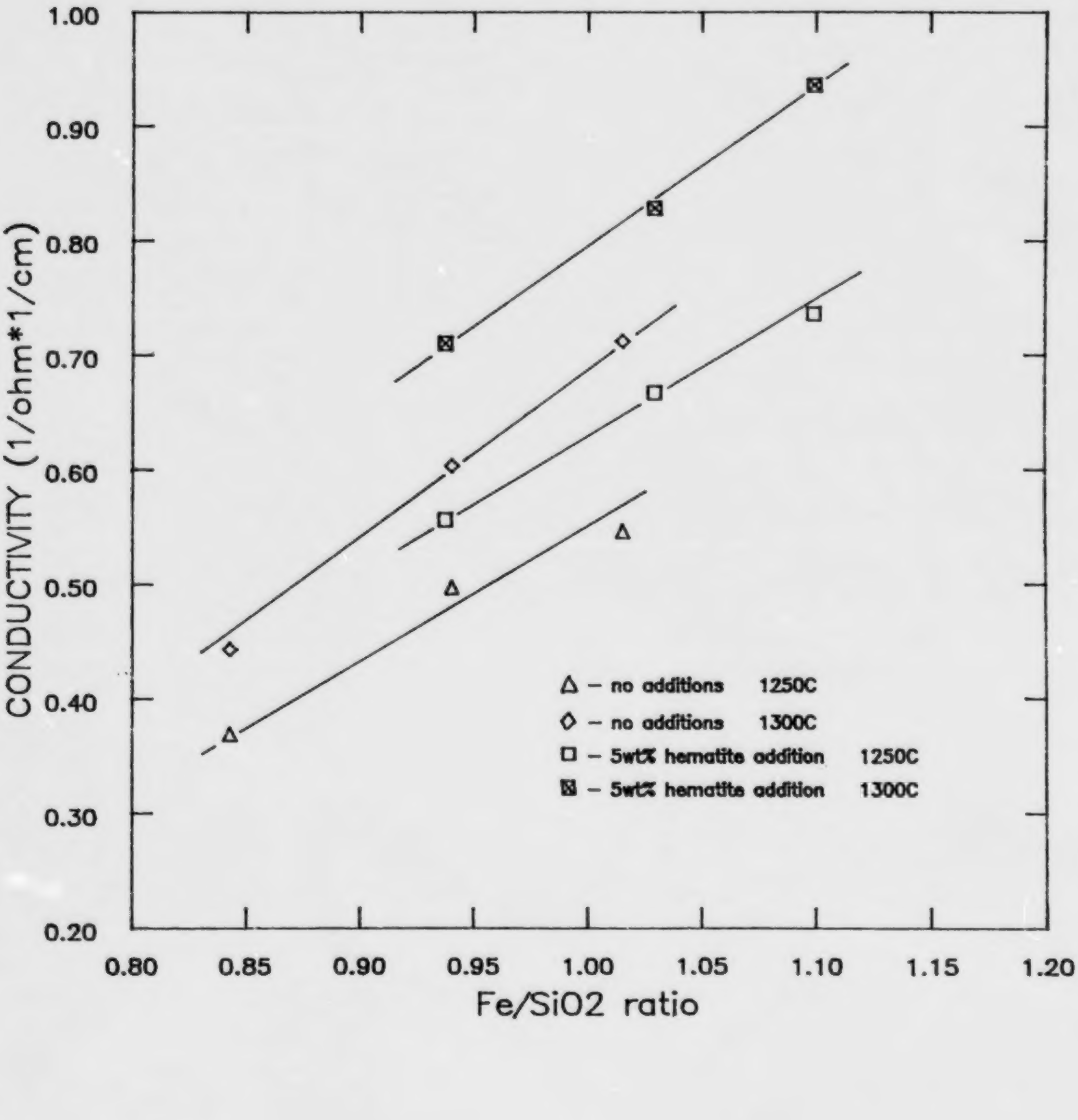


Figure 5: Effect of Fe/SiO_2 Ratio and Hematite Addition on Electrical Conductivity

Figure 6 shows the effect of CaO additions on the conductivity of the slag. The conductivity values were plotted against the total CaO content of the sample based on its final chemical analysis. From Figure 6, it appears that the addition of CaO additions increase the electrical conductivity of the slag. Due to the limited number of data points, a linear relationship was assumed. More experiments need to be performed to determine if the curves level off with higher CaO additions. Mori and Matsushita have found that the electrical conductivity in the binary $CaO-SiO_2$ system levels off with high CaO additions.

After the tests several slag samples were analyzed for their molybdenum content. The slags contained between 0.2 and 0.7% Mo. These levels are similar to those obtained by Victorovich et al. It is unlikely that these low levels will significantly influence the results obtained in this investigation.

Experiments to determine the silica saturation boundary of the slag could not be performed due to the limitations of the apparatus. Since the thermocouple was located outside of the sample, it was difficult to determine the actual melt temperature as the furnace was cooling.

SUMMARY

The results of these experiments indicate that increases in temperature, iron content, oxygen potential, and CaO additions all tend to increase the electrical conductivity of the slag.

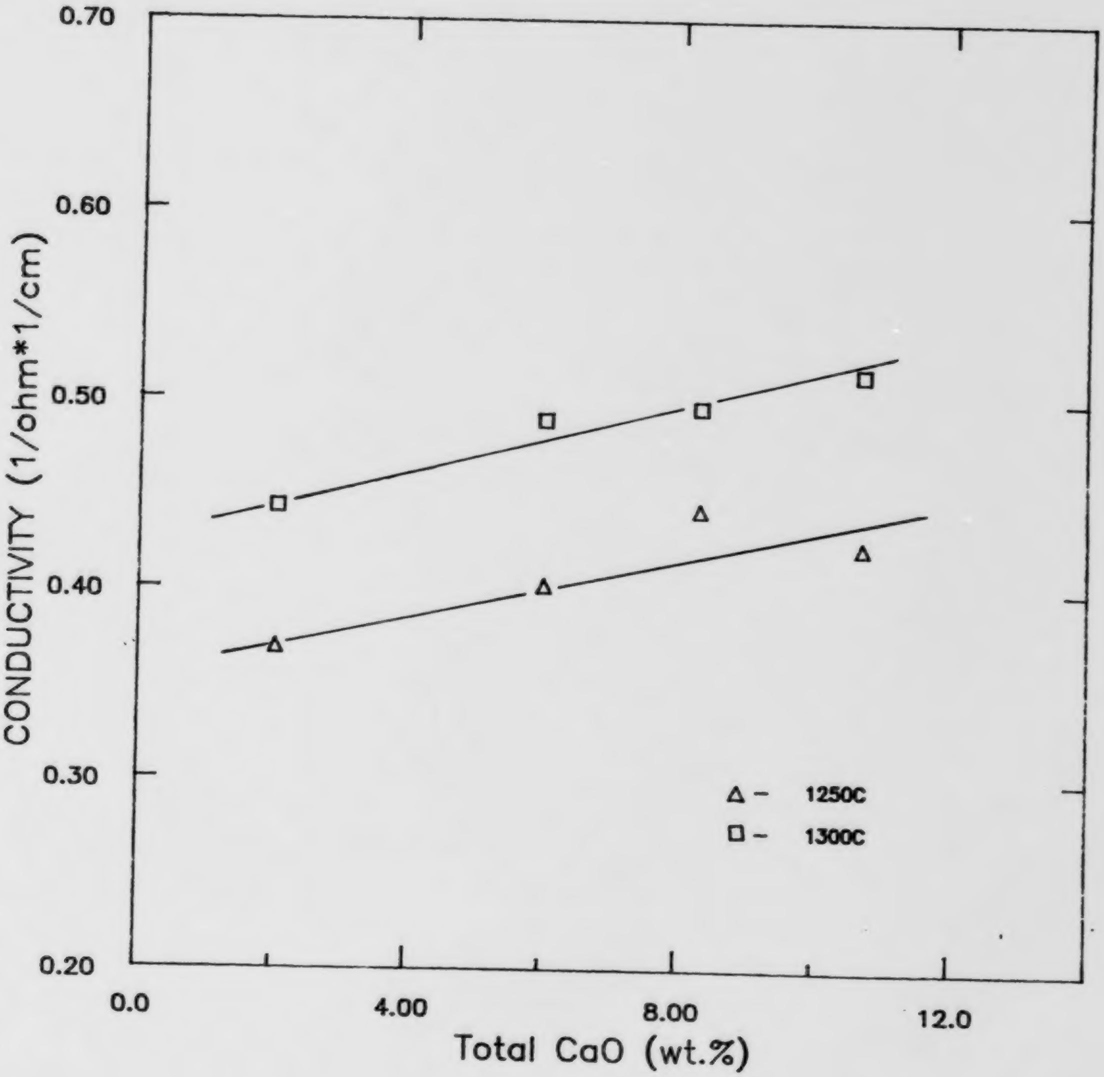


Figure 6: Effect of CaO Additions on Electrical Conductivity

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1. G. S. Victorovich, C. Diaz, and D. K. Vallbacka: "Electrical Conductivity of Ferromagnesian Silicates", in Second International Symposium on Metallurgical Slags and Fluxes (H. A. Fine and D. R. Gaskell, eds.), TMS-AIME, 1984, pp 907-924.

2. K. Mori and Y. Matsushita: "The Electrical Conductivity of Molten Binary Slags" Tetsu-to-Hagane, Volume 38(5), 1952, pp 6-11.

APPENDIX I

DATA FOR ELECTRICAL CONDUCTIVITY MEASUREMENTS

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2

DATE: DEC. 3/87

Additions made to sample:

4.57 g SiO_2 to 100 g as-received slag

Atm.: High purity Ar (gettered).

Total wt. of sample: 104.57 g

Total wt. w/crucible: init.- 151.50 g
finl.- 151.44 g

RUN#: 1

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	122	0.0	5.7 ~~[illegible]~~
3	83	4.95	1.8
3	63	7.49	1.3
3	43	10.03	1.0
1	33	11.3	0.91
1	23	12.57	0.84
1	13	13.84	0.76
1	03	15.11	0.70
1	993	16.38	0.66
1	983	17.65	0.61
1	973	18.92	0.58
1	963	20.19	0.54
1	953	21.46	0.51
1	943	22.73	0.48
1	933	24.0	0.45
1	923	25.27	0.43
1	913	26.54	0.39
1	903	27.81	0.345
1 —	893 —	29.08 —	0.06 — BOTTOM —
	DEPTH. —	29.0 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 3/87

SLAG SAMPLE: 0.85 Fe/SiO_2

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω **RUN#:** 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	——	5.7	——
4.95	——	1.8	——
7.49	——	1.3	——
10.03	0.305	1.0	0.324
11.3	0.284	0.91	0.334
12.57	0.265	0.84	0.340
13.84	0.247	0.76	0.353
15.11	0.230	0.70	0.359
16.38	0.214	0.66	0.357
17.65	0.199	0.61	0.362
18.92	0.186	0.58	0.358
20.19	0.174	0.54	0.363
21.46	0.164	0.51	0.364
22.73	0.154	0.48	0.367
24.0	0.146	0.45	0.374
25.27	0.139	0.43	0.376
26.54	——	0.39	——
27.81	——	0.345	——
29.08	——	——	——

wide – 0.357 ± 0.012

narrow – 0.358 ± 0.003

X

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2

DATE: DEC. 3/87

Additions made to sample:

4.57 g SiO_2 to 100g as-received slag

Atm.: High purity Ar (gettered)

Total wt. of sample: 104.57

Total wt. w/crucible: init.- 151.50g
finl.- 151.44g

RUN#: 2

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	122	0.0	4.7
3	83	4.95	1.6
3	63	7.49	1.2
1	43	10.03	0.95
1	33	11.3	0.86
1	23	12.57	0.80
1	13	13.84	0.74
1	03	15.11	0.69
1	993	16.38	0.64
1	983	17.65	0.60
1	973	18.92	0.56
1	963	20.19	0.52
1	953	21.46	0.50
1	943	22.73	0.46
1	933	24.0	0.44
1	923	25.27	0.41
1	913	26.54	0.38
1	903	27.81	0.32
1 —	— 893 —	— 29.08 —	— 0.06 — BOTTOM —
		Depth - 29.0 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 3/87

SLAG SAMPLE: 0.85 Fe/SiO_2

Atm.: H.P.Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	4.7	—
4.95	—	1.6	—
7.49	—	1.2	—
10.03	0.305	0.95	0.343
11.3	0.284	0.86	0.355
12.57	0.265	0.80	0.358
13.84	0.247	0.74	0.363
15.11	0.230	0.69	0.365
16.38	0.214	0.64	0.369
17.65	0.199	0.60	0.369
18.92	0.186	0.56	0.372
20.19	0.174	0.52	0.378
21.46	0.164	0.50	0.373
22.73	0.154	0.46	0.385
24.0	0.146	0.44	0.384
25.27	0.139	0.41	0.397
26.54	—	0.38	—
27.81	—	0.32	—
29.08	—	—	—

wide – 0.370 ± 0.010

narrow – 0.368 ± 0.004

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2

DATE: DEC. 3/87

Additions made to sample:

4.57 g SiO_2 to 100 g as-received slag

Atm.: High purity Ar (gettered)

Total wt. of sample: 104.57g

Total wt. w/crucible: init.- 151.50g

finl.- 151.44g

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	122	0.0	5.2
3	83	4.95	1.6
3	63	7.49	1.2
1	43	10.03	0.96
1	33	11.3	0.86
1	23	12.57	0.80
1	13	13.84	0.73
1	03	15.11	0.68
1	993	16.38	0.64
1	983	17.65	0.59
1	973	18.92	0.56
1	963	20.19	0.53
1	953	21.46	0.49
1	943	22.73	0.47
1	933	24.0	0.44
1	923	25.27	0.~~3~~41
1	913	26.54	0.38
1	903	27.81	0.33
1	893	29.08	0.06 – BOTTOM
		Depth = 29.0 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 3/07.

SLAG SAMPLE: 0.85 Fe/SiO_2

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	5.2	—
4.95	—	1.6	—
7.49	—	1.2	—
10.03	0.305	0.96	0.339
11.3	0.284	0.86	0.355
12.57	0.265	0.80	0.358
13.84	0.247	0.73	0.369
15.11	0.230	0.68	0.371
16.38	0.214	0.64	0.369
17.65	0.199	0.59	0.375
18.92	0.186	0.56	0.372
20.19	0.174	0.53	0.370
21.46	0.164	0.49	0.381
22.73	0.154	0.47	0.376
24.0	0.146	0.44	0.384
25.27	0.139	0.41	0.397
26.54	—	0.38	—
27.81	—	0.33	—
29.08	—	—	—

wide – 0.371 ± 0.009

narrow – 0.371 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 3/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar

SLAG SAMPLE: 0.85 Fe/SiO$_2$

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#2+3).
	RUN# 1	RUN# 2	RUN# 3	
0.0	5.7	4.7	5.2	4.95
4.95	1.8	1.6	1.6	1.60
7.49	1.3	1.2	1.2	1.20
10.03	1.0	0.95	0.96	0.955
11.3	0.91	0.86	0.86	0.877
12.57	0.84	0.80	0.80	0.800
13.84	0.76	0.74	0.73	0.735
15.11	0.70	0.69	0.68	0.685
16.38	0.66	0.64	0.64	0.640
17.65	0.61	0.60	0.59	0.595
18.92	0.58	0.56	0.56	0.560
20.19	0.54	0.52	0.53	0.525
21.46	0.51	0.50	0.49	0.495
22.73	0.48	0.46	0.47	0.465
24.0	0.45	0.44	0.44	0.440
25.27	0.43	0.41	0.41	0.410
26.54	0.39	0.38	0.38	0.380
27.81	0.345	0.32	0.33	0.325
29.08 —	0.06 —	0.06 —	0.06 —	0.06 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 3/87

Atm.: HP. Ar.

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	4.95	—
4.95	—	1.60	—
7.49	—	1.20	—
10.03	0.305	0.955	0.341
11.3	0.284	0.877	0.348
12.57	0.265	0.800	0.358
13.84	0.247	0.735	0.366
15.11	0.230	0.685	0.368
16.38	0.214	0.640	0.369
17.65	0.199	0.595	0.372
18.92	0.186	0.560	0.372
20.19	0.174	0.525	0.374
21.46	0.164	0.495	0.377
22.73	0.154	0.465	0.380
24.0	0.146	0.440	0.384
25.27	0.139	0.410	0.397.
26.54	—	0.380	—
27.81	—	0.325	—
29.08	—	—	—

wide - 0.370 ± 0.010

narrow - 0.369 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 3/87

Atm.: H.P. Ar

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	5.7	4.7	5.2	5.2
4.95	1.8	1.6	1.6	1.67
7.49	1.3	1.2	1.2	1.23
10.03	1.0	0.95	0.96	0.970
11.3	0.91	0.86	0.86	0.877
12.57	0.84	0.80	0.80	0.813
13.84	0.76	0.74	0.73	0.743
15.11	0.70	0.69	0.68	0.690
16.38	0.66	0.64	0.64	0.647
17.65	0.61	0.60	0.59	0.600
18.92	0.58	0.56	0.56	0.567
20.19	0.54	0.52	0.53	0.530
21.46	0.51	0.50	0.49	0.500
22.73	0.48	0.46	0.47	0.470
24.0	0.45	0.44	0.44	0.443
25.27	0.43	0.41	0.41	0.417
26.54	0.39	0.38	0.38	0.383
27.81	0.345	0.32	0.33	0.332
29.08	0.06	0.06	0.06	0.06 Rest.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 3/87

SLAG SAMPLE: $0.85\ Fe/SiO_2$

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	5.2	—
4.95	—	1.67	—
7.49	—	1.23	—
10.03	0.305	0.970	0.335
11.3	0.284	0.877	0.348
12.57	0.265	0.813	0.352
13.84	0.247	0.743	0.362
15.11	0.230	0.690	0.365
16.38	0.214	0.647	0.365
17.65	0.199	0.600	0.369
18.92	0.186	0.567	0.367
20.19	0.174	0.530	0.370
21.46	0.164	0.500	0.373
22.73	0.154	0.470	0.376
24.0	0.146	0.443	0.381
25.27	0.139	0.417	0.389
26.54	—	0.383	—
27.81	—	0.332	—
29.08	—	—	—

wide – 0.366 ± 0.010

narrow – 0.366 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2

DATE: DEC. 3/87

Additions made to sample:

4.57 g SiO_2 to 100g as-received slag.

Atm.: High purity Ar (gettered)

Total wt. of sample: 104.57g

Total wt. w/crucible: init.- 151.50g

finl.- 151.44g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	121	0.0	3.5
3	82	4.95	1.45
3	62	7.49	1.05
1	42	10.03	0.84
1	32	11.3	0.76
1	22	12.57	0.70
1	12	13.84	0.64
1	02	15.11	0.60
1	992	16.38	0.56
1	982	17.65	0.52
1	972	18.92	0.47
1	962	20.19	0.45
1	952	21.46	0.425
1	942	22.73	0.40
1	932	24.0	0.38
1	922	25.27	0.355
1	912	26.54	0.33
1	902	27.81	0.28
1 —	892 —	29.08 —	0.06 – BOTTOM —
		Depth. = 29.0 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 3/87

Atm.: H.P. Ar.

$r_{ext.}$ = 0.06 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY (ohm^{-1}.cm^{-1})
0.0	—	3.5	—
4.95	—	1.45	—
7.49	—	1.05	—
10.03	0.305	0.84	0.391
11.3	0.284	0.76	0.406
12.57	0.265	0.70	0.414
13.84	0.247	0.64	0.426
15.11	0.230	0.60	0.426
16.38	0.214	0.56	0.428
17.65	0.199	0.52	0.433
18.92	0.186	0.47	0.454
20.19	0.174	0.45	0.446
21.46	0.164	0.425	0.449
22.73	0.154	0.40	0.453
24.0	0.146	0.38	0.456
25.27	0.139	0.355	0.471
26.54	—	0.33	—
27.81	—	0.28	—
29.08	—	—	—

wide – 0.436 ± 0.017

narrow – 0.437 ± 0.012

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2

DATE: DEC. 3/87

Additions made to sample:

4.57 g SiO_2 to 100 g as-received slag

Atm.: High purity Ar (gettered)

Total wt. of sample: 104.57 g

Total wt. w/crucible: init.- 151.50 g

finl.- 151.44 g

RUN#: 2

TEMPERATURE: 1300 °C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	121	0.0	3.6
3	82	4.95	1.32
1	62	7.49	0.98
1	42	10.03	0.79
1	32	11.3	0.72
1	22	12.57	0.66
1	12	13.84	0.60
1	02	15.11	0.56
1	992	16.38	0.52
1	982	17.65	0.49
1	972	18.92	0.46
1	962	20.19	0.43
1	952	21.46	0.41
1	942	22.73	0.385
1	932	24.0	0.36
1	922	25.27	0.34
1	912	26.54	0.31
1	902	27.81	0.26
1	892	29.08	0.04 – BOTTOM
		Depth - 29.0 mm	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 3/87

Atm.: AP. Ar

$r_{ext.}$ = 0.04Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.6	—
4.95	—	1.32	—
7.49	—	0.98	—
10.03	0.305	0.79	0.407
11.3	0.284	0.72	0.418
12.57	0.265	0.66	0.427
13.84	0.247	0.60	0.441
15.11	0.230	0.56	0.442
16.38	0.214	0.52	0.446
17.65	0.199	0.49	0.442
18.92	0.186	0.46	0.443
20.19	0.174	0.43	0.446
21.46	0.164	0.41	0.443
22.73	0.154	0.385	0.446
24.0	0.146	0.36	0.456
25.27	0.139	0.34	0.463
26.54	—	0.31	—
27.81	—	0.26	—
29.08	—	—	—

wide – 0.441 ± 0.010

narrow – 0.444 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2

DATE: DEC. 3/87

Additions made to sample:

4.57 g SiO_2 to 100 g as-received slag.

Atm.: High purity Ar (getered)

Total wt. of sample: 104.57 g

Total wt. w/crucible: init.- 151.50 g
finl.- 151.44 g

RUN#: 3

TEMPERATURE: 1300 °C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	121	0.0	3.7
3	82	4.95	1.3
3	62	7.49	0.95
1	42	10.03	0.80
1	32	11.3	0.72
1	22	12.57	0.66
1	12	13.84	0.60
1	02	15.11	0.56
1	992	16.38	0.52
1	982	17.65	0.49
1	972	18.92	0.46
1	962	20.19	0.435
1	952	21.46	0.405
1	942	22.73	0.385
1	932	24.0	0.35
1	922	25.27	0.34
1	912	26.54	0 ~~35~~.31
1	902	27.81	0.26
1	892	29.08	0.04 - BOTTOM
		Depth = 29.0 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 3/87

SLAG SAMPLE: 0.85 Fe/SiO$_2$

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.04Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY (ohm^{-1}.cm^{-1})
0.0	———	3.7	———
4.95	———	1.3	———
7.49	———	0.95	———
10.03	0.305	0.80	0.401
11.3	0.284	0.72	0.418
12.57	0.265	0.66	0.427
13.84	0.247	0.60	0.441
15.11	0.230	0.56	0.442
16.38	0.214	0.52	0.446
17.65	0.199	0.49	0.442
18.92	0.186	0.46	0.443
20.19	0.174	0.435	0.441
21.46	0.164	0.405	0.449
22.73	0.154	0.385	0.446
24.0	0.146	0.35	0.471
25.27	0.139	0.34	0.463
26.54	———	0.31	———
27.81	———	0.26	———
29.08	———	———	———

wide – 0.442 ± 0.013

narrow – 0.443 ± 0.002

x

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 3/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: High purity Ar (gettered).

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1300 °C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#2+3 only)
	RUN# 1	RUN# 2	RUN# 3	
0.0	3.54	3.6	3.7	3.65
4.95	1.45	1.32	1.3	1.31
7.49	1.05	0.98	0.95	0.965
10.03	0.84	0.79	0.80	0.795
11.3	0.76	0.72	0.72	0.72
12.57	0.70	0.66	0.66	0.66
13.84	0.64	0.60	0.60	0.60
15.11	0.60	0.56	0.56	0.56
16.38	0.56	0.52	0.52	0.52
17.65	0.52	0.49	0.49	0.49
18.92	0.47	0.46	0.46	0.46
20.19	0.45	0.43	0.435	0.4325
21.46	0.425	0.41	0.405	0.4075
22.73	0.40	0.385	0.385	0.385
24.0	0.38	0.36	0.35	0.355
25.27	0.355	0.34	0.34	0.34
26.54	0.33	0.31	0.31	0.31
27.81	0.28	0.26	0.26	0.26
29.08	0.06 —	0.04 —	0.04 —	0.04 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 3/87

SLAG SAMPLE: 0.85 Fe/SiO_2

Atm.: High purity Ar (gettered).

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.04 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.65	—
4.95	—	1.31	—
7.49	—	0.965	—
10.03	0.305	0.795	0.404
11.3	0.284	0.72	0.418
12.57	0.265	0.66	0.427
13.84	0.247	0.60	0.441
15.11	0.230	0.56	0.442
16.38	0.214	0.52	0.446
17.65	0.199	0.49	0.442
18.92	0.186	0.46	0.443
20.19	0.174	0.4325	0.443
21.46	0.164	0.4075	0.446
22.73	0.154	0.385	0.446
24.0	0.146	0.355	0.463
25.27	0.139	0.34	0.463
26.54	—	0.31	—
27.81	—	0.26	—
29.08	—	0.04	—

wide – 0.442 ± 0.011

narrow – 0.443 ± 0.0016

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 3/87

Atm.: H.P. Ar.

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	3.5	3.6	3.7	3.60
4.95	1.45	1.32	1.3	1.357
7.49	1.05	0.98	0.95	0.993
10.03	0.84	0.79	0.80	0.810
11.3	0.76	0.72	0.72	0.733
12.57	0.70	0.66	0.66	0.673
13.84	0.64	0.60	0.60	0.613
15.11	0.60	0.56	0.56	0.573
16.38	0.56	0.52	0.52	0.533
17.65	0.52	0.49	0.49	0.500
18.92	0.47	0.46	0.46	0.463
20.19	0.45	0.43	0.435	0.438
21.46	0.425	0.41	0.405	0.413
22.73	0.40	0.385	0.385	0.390
24.0	0.38	0.36	0.35	0.363
25.27	0.355	0.34	0.34	0.345
26.54	0.33	0.31	0.31	0.317
27.81	0.28	0.26	0.26	0.267
29.08	0.06	0.04	0.04	0.047

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2

TEMPERATURE: 1300 °C ± 5°

DATE: DEC. 3/87

Atm.: H.P. Ar.

$r_{ext.}$ = 0.047 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.60	—
4.95	—	1.357	—
7.49	—	0.993	—
10.03	0.305	0.810	0.400
11.3	0.284	0.733	0.414
12.57	0.265	0.673	0.423
13.84	0.247	0.613	0.436
15.11	0.230	0.573	0.437
16.38	0.214	0.533	0.440
17.65	0.199	0.500	0.439
18.92	0.186	0.463	0.447
20.19	0.174	0.438	0.445
21.46	0.164	0.413	0.448
22.73	0.154	0.390	0.449
24.0	0.146	0.363	0.462
25.27	0.139	0.345	0.466
26.54	—	0.317	—
27.81	—	0.267	—
29.08	—	—	—

wide – 0.440 ± 0.013

narrow – 0.442 ± 0.004

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt% Fe_2O_3 DATE: DEC. 6/87

Additions made to sample: Atm.: H.P. Ar (gettered).

100g as-received + 4.57g SiO_2 + 5.23g Fe_2O_3

Total wt. of sample: 109.80g Total wt. w/crucible: init.- 159.51g

finl.- 159.34g

RUN#: 1 TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10(3)	116	0.0	2.5 (2.85)
3	77	4.95	0.95
1	57	7.49	0.78
1	37	10.03	0.63
1	27	11.3	0.58
1	17	12.57	0.525
1	07	13.84	0.485
1	997	15.11	0.445
1	987	16.38	0.42
1	977	17.65	0.385
1	967	18.92	0.36
1	957	20.19	0.34
1	947	21.46	0.32
1	937	22.73	0.30
1	927	24.0	0.28
1	917	25.27	0.26
1	907	26.54	0.245
1	897	27.81	0.22
1	887	29.08	0.16
1	877	30.35	0.03 - BOTTOM
		Depth = 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 6/87

Atm.: U.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.85	—
4.95	—	0.95	—
7.49	—	0.78	—
10.03	0.305	0.63	0.508
11.3	0.284	0.58	0.516
12.57	0.265	0.525	0.535
13.84	0.247	0.485	0.543
15.11	0.230	0.445	0.554
16.38	0.214	0.42	0.549
17.65	0.199	0.385	0.561
18.92	0.186	0.36	0.564
20.19	0.174	0.34	0.561
21.46	0.164	0.32	0.566
22.73	0.154	0.30	0.570
24.0	0.146	0.28	0.584
25.27	0.139	0.26	0.604
26.54	—	0.245	—
27.81	—	0.22	—
29.08	—	0.16	—

wide – 0.555 ± 0.019

narrow – 0.558 ± 0.006

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt% Fe_2O_3

DATE: DEC. 6/87

Additions made to sample:

100 g as-received + 4.57 g SiO_2 + 5.23 g Fe_2O_3

Atm.: H.P. Ar (gettered).

Total wt. of sample: 109.80 g

Total wt. w/crucible: init.- 159.51 g

finl.- 159.34 g

RUN#: 2

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	116	0.0	2.85
3	77	4.95	0.95
1	57	7.49	0.80
1	37	10.03	0.64
1	27	11.3	0.58
1	17	12.57	0.53
1	07	13.84	0.49
1	997	15.11	0.445
1	987	16.38	0.42
1	977	17.65	0.39
1	967	18.92	0.365
1	957	20.19	0.34
1	947	21.46	0.32
1	937	22.73	0.30
1	927	24.0	0.285
1	917	25.27	0.265
1	907	26.54	0.25
1	897	27.81	0.22
1	887	29.08	0.18
1	877	30.35	0.03- BOTTOM.
		Depth = 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.85	—
4.95	—	0.95	—
7.49	—	0.80	—
10.03	0.305	0.64	0.500
11.3	0.284	0.58	0.516
12.57	0.265	0.53	0.530
13.84	0.247	0.49	0.537
15.11	0.230	0.445	0.554
16.38	0.214	0.42	0.549
17.65	0.199	0.39	0.553
18.92	0.186	0.365	0.555
20.19	0.174	0.34	0.561
21.46	0.164	0.32	0.566
22.73	0.154	0.30	0.570
24.0	0.146	0.285	0.573
25.27	0.139	0.265	0.591
26.54	—	0.25	—
27.81	—	0.22	—
29.08	—	0.18	—

wide – 0.551 ± 0.018

narrow – 0.554 ± 0.004

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 6/87

Additions made to sample:

100 g as-received + 4.57g SiO_2 + 5.23g Fe_2O_3

Atm.: H.P. Ar (gettered)

Total wt. of sample: 109.80g

Total wt. w/crucible: init.- 159.51g.

finl.- 159.34g

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	114	0.0	2.7
3	75	4.95	0.96
1	55	7.49	0.80
1	35	10.03	0.65
1	25	11.3	0.59
1	15	12.57	0.54
1	05	13.84	0.50
1	995	15.11	0.465
1	985	16.38	0.435
1	975	17.65	0.40
1	965	18.92	0.375
1	955	20.19	0.35
1	945	21.46	0.33
1	935	22.73	0.31
1	925	24.0	0.29
1	915	25.27	0.27
1	905	26.54	0.25
1	895	27.81	0.225
1	885	29.08	0.18
1	875	30.35	0.03 - BOTTOM
		Depth. = 30.35mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt% Fe_2O_3

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.7	—
4.95	—	0.96	—
7.49	—	0.80	—
10.03	0.305	0.65	0.492
11.3	0.284	0.59	0.507
12.57	0.265	0.54	0.520
13.84	0.247	0.50	0.526
15.11	0.230	0.465	0.529
16.38	0.214	0.435	0.528
17.65	0.199	0.40	0.538
18.92	0.186	0.375	0.539
20.19	0.174	0.35	0.544
21.46	0.164	0.33	0.547
22.73	0.154	0.31	0.550
24.0	0.146	0.29	0.562
25.27	0.139	0.27	0.579
26.54	—	0.25	—
27.81	—	0.225	—
29.08	—	0.18	—

wide – 0.535 ± 0.015

narrow – 0.536 ± 0.007

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 6/87

Atm.: HP. Ar.

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#1+2)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.85	2.85	2.7	2.85
4.95	0.95	0.95	0.96	0.950
7.49	0.78	0.80	0.80	0.790
10.03	0.63	0.64	0.65	0.635
11.3	0.58	0.58	0.59	0.580
12.57	0.525	0.53	0.54	0.528
13.84	0.485	0.49	0.50	0.488
15.11	0.445	0.445	0.465	0.445
16.38	0.42	0.42	0.435	0.420
17.65	0.385	0.39	0.40	0.388
18.92	0.36	0.365	0.375	0.363
20.19	0.34	0.34	0.35	0.340
21.46	0.32	0.32	0.33	0.320
22.73	0.30	0.30	0.31	0.300
24.0	0.28	0.285	0.29	0.285
25.27	0.26	0.265	0.27	0.263
26.54	0.245	0.25	0.25	0.248
27.81	0.22	0.22	0.225	0.220
29.08	0.16	0.18	0.18	0.170
30.35	0.03 ——	0.03 ——	0.03 ——	0.03 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: HP. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (*1+2)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.85	—
4.95	—	0.950	—
7.49	—	0.790	—
10.03	0.305	0.635	0.504
11.3	0.284	0.580	0.516
12.57	0.265	0.528	0.532
13.84	0.247	0.488	0.539
15.11	0.230	0.445	0.554
16.38	0.214	0.420	0.549
17.65	0.199	0.388	0.556
18.92	0.186	0.363	0.559
20.19	0.174	0.340	0.561
21.46	0.164	0.320	0.566
22.73	0.154	0.300	0.570
24.0	0.146	0.285	0.573
25.27	0.139	0.263	0.597
26.54	—	0.248	—
27.81	—	0.220	—
29.08	—	0.170	—

wide - 0.552 ± 0.017

narrow - 0.556 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 6/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: A.P. Ar.

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.85	2.85	2.7	2.80
4.95	0.95	0.95	0.96	0.953
7.49	0.78	0.80	0.80	0.793
10.03	0.63	0.64	0.65	0.640
11.3	0.58	0.58	0.59	0.583
12.57	0.525	0.53	0.54	0.532
13.84	0.485	0.49	0.50	0.492
15.11	0.445	0.445	0.465	0.452
16.38	0.42	0.42	0.435	0.425
17.65	0.385	0.39	0.40	0.392
18.92	0.36	0.365	0.375	0.367
20.19	0.34	0.34	0.35	0.343
21.46	0.32	0.32	0.33	0.323
22.73	0.30	0.30	0.31	0.303
24.0	0.28	0.285	0.29	0.285
25.27	0.26	0.265	0.27	0.265
26.54	0.245	0.25	0.25	0.248
27.81	0.22	0.22	0.225	0.222
29.08	0.16	0.18	0.18	0.173
30.35	0.03 —	0.03 —	0.03 —	0.03 R_{ext}

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.80	———
4.95	———	0.953	———
7.49	———	0.793	———
10.03	0.305	0.640	0.500
11.3	0.284	0.583	0.514
12.57	0.265	0.532	0.528
13.84	0.247	0.492	0.535
15.11	0.230	0.452	0.545
16.38	0.214	0.425	0.542
17.65	0.199	0.392	0.550
18.92	0.186	0.367	0.552
20.19	0.174	0.343	0.556
21.46	0.164	0.323	0.560
22.73	0.154	0.303	0.564
24.0	0.146	0.285	0.573
25.27	0.139	0.265	0.591
26.54	———	0.248	———
27.81	———	0.222	———
29.08	———	0.173	———

wide – 0.547 ± 0.017

narrow – 0.549 ± 0.006.

SLAG CONDUCTIVITY DETERMINATION X

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 6/87

Additions made to sample:

100g as-received + 4.57 SiO_2 + 5.23g Fe_2O_3

Atm.: H.P. Ar (gettered)

Total wt. of sample: 109.80g

Total wt. w/crucible: init.- 159.51g

finl.- 159.34g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	112	0.0	2.25
1	73	4.95	0.90
1	53	7.49	0.70
1	33	10.03	0.58
1	23	11.3	0.55
1	13	12.57	0.495
1	03	13.84	0.46
1	993	15.11	0.425
1	983	16.38	0.40
1	973	17.65	0.375
1	963	18.92	0.355
1	953	20.19	[illegible] 0.335
1	943	21.46	0.315
1	933	22.73	0.30
1	923	24.0	0.28
1	913	25.27	0.265
1	903	26.54	0.245
1	893	27.81	0.22
1	883	29.08	0.13
1 —	873 —	30.35 —	0.10 — BOTTOM.
		Depth = 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.10 Ω RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	——	2.25	——
4.95	——	0.90	——
7.49	——	0.70	——
10.03	0.305	0.58	0.635
11.3	0.284	0.55	0.631
12.57	0.265	0.495	0.671
13.84	0.247	0.46	0.686
15.11	0.230	0.425	0.708
16.38	0.214	0.40	0.713
17.65	0.199	0.375	0.724
18.92	0.186	0.355	0.729
20.19	0.174	0.335	0.740
21.46	0.164	0.315	0.763
22.73	0.154	0.30	0.770
24.0	0.146	0.28	0.811
25.27	0.139	0.265	0.842
26.54	——	0.245	——
27.81	——	0.22	——
29.08	——	0.13	——

wide – 0.722 ± 0.050

narrow – 0.723 ± 0.013

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO$_2$ with 5 wt.% Fe$_2$O$_3$

DATE: DEC. 6/87

Additions made to sample:

100 g as-received + 4.57 SiO$_2$ + 5.23 g Fe$_2$O$_3$

Atm.: A.P. Ar (gettered).

Total wt. of sample: 109.80 g

Total wt. w/crucible: init.- 159.51 g

finl.- 159.34 g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	114	0.0	2.30
1	75	4.95	0.925
1	55	7.49	0.72
1	35	10.03	0.59
1	25	11.3	0.54
1	15	12.57	0.495
1	05	13.84	0.455
1	995	15.11	0.42
1	985	16.38	0.39
1	975	17.65	0.365
1	965	18.92	0.34
1	955	20.19	0.32
1	945	21.46	0.30
1	935	22.73	0.285
1	925	24.0	0.270
1	915	25.27	0.25
1	905	26.54	0.235
1	895	27.81	0.21
1	885	29.08	0.17
1	—	BOTTOM. —	0.08
		Depth = 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω **RUN#:** 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.30	———
4.95	———	0.925	———
7.49	———	0.72	———
10.03	0.305	0.59	0.598
11.3	0.284	0.54	0.617
12.57	0.265	0.495	0.639
13.84	0.247	0.455	0.659
15.11	0.230	0.42	0.676
16.38	0.214	0.39	0.690
17.65	0.199	0.365	0.698
18.92	0.186	0.34	0.715
20.19	0.174	0.32	0.725
21.46	0.164	0.30	0.745
22.73	0.154	0.285	0.751
24.0	0.146	0.270	0.768
25.27	0.139	0.25	0.818
26.54	———	0.235	———
27.81	———	0.21	———
29.08	———	0.17	———

wide - 0.698 ± 0.048

narrow - 0.701 ± 0.020

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 6/87

Additions made to sample:

100g as-received + 4.57g SiO_2 + 5.23g Fe_2O_3

Atm.: H.P. Ar (gettered)

Total wt. of sample: 109.80g

Total wt. w/crucible: init.- 159.51g

finl.- 159.34g

RUN#: 3

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	114	0.0	2.40
1	75	4.95	0.96
1	55	7.49	0.745
1	35	10.03	0.615
1	25	11.3	0.565
1	15	12.57	0.525
1	05	13.84	0.485
1	995	15.11	0.455
1	985	16.38	0.43
1	975	17.65	0.40
1	965	18.92	0.38
1	955	20.19	0.36
1	945	21.46	0.34
1	935	22.73	0.32
1	925	24.0	0.305
1	915	25.27	0.29
1	905	26.54	0.27
1	895	27.81	0.25
1	885	29.08	0.21
1	BOTTOM		0.10
		Depth = 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.10 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1} \cdot cm^{-1}$)
0.0	——	2.40	——
4.95	——	0.96	——
7.49	——	0.745	——
10.03	0.305	0.615	0.592
11.3	0.284	0.565	0.611
12.57	0.265	0.525	0.624
13.84	0.247	0.485	0.642
15.11	0.230	0.455	0.648
16.38	0.214	0.43	0.648
17.65	0.199	0.40	0.663
18.92	0.186	0.38	0.664
20.19	0.174	0.36	0.669
21.46	0.164	0.34	0.683
22.73	0.154	0.32	0.700
24.0	0.146	0.305	0.712
25.27	0.139	0.29	0.732
26.54	——	0.27	——
27.81	——	0.25	——
29.08	——	0.21	——

wide – 0.660 ± 0.030

narrow – 0.658 ± 0.010

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 6/87

Atm.: H.P. Ar (gettered)

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#1+2 only)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.25	2.30	2.40	2.275
4.95	0.90	0.925	0.96	0.9125
7.49	0.70	0.72	0.745	0.71
10.03	0.58	0.59	0.615	0.585
11.3	0.55	0.54	0.565	0.545
12.57	0.495	0.495	0.525	0.495
13.84	0.46	0.455	0.485	0.455
15.11	0.425	0.42	0.455	0.422
16.38	0.40	0.39	0.43	0.395
17.65	0.375	0.365	0.40	0.37
18.92	0.355	0.34	0.38	0.3475
20.19	0.335	0.32	0.36	0.330
21.46	0.315	0.30	0.34	0.310
22.73	0.30	0.285	0.32	0.2925
24.0	0.28	0.270	0.305	0.275
25.27	0.265	0.25	0.29	0.2575
26.54	0.245	0.235	0.27	0.240
27.81	0.22	0.210	0.25	0.215
29.08	0.13	0.170	0.21	0.15
30.35	0.10	0.08	0.10	0.09 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION: (

DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: U.P. Ar (Gettered).

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.09 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#1+2)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.275	—
4.95	—	0.913	—
7.49	—	0.710	—
10.03	0.305	0.585	0.616
11.3	0.284	0.545	0.624
12.57	0.265	0.495	0.654
13.84	0.247	0.455	0.677
15.11	0.230	0.422	0.693
16.38	0.214	0.395	0.702
17.65	0.199	0.370	0.711
18.92	0.186	0.348	0.721
20.19	0.174	0.330	0.725
21.46	0.164	0.310	0.745
22.73	0.154	0.293	0.759
24.0	0.146	0.275	0.789
25.27	0.139	0.258	0.827
26.54	—	0.240	—
27.81	—	0.215	—
29.08	—	0.15	—
30.35	—	0.09	—

wide – 0.708 ± 0.048

narrow – 0.710 ± 0.013

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1300°C ± 5°

DATE: DEC.6/87
Atm.: H.P. Ar

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.25	2.30	2.40	2.32
4.95	0.90	0.925	0.96	0.928
7.49	0.70	0.72	0.745	0.722
10.03	0.58	0.59	0.615	0.595
11.3	0.55	0.54	0.565	0.552
12.57	0.495	0.495	0.525	0.505
13.84	0.46	0.455	0.485	0.467
15.11	0.425	0.42	0.455	0.433
16.38	0.40	0.39	0.43	0.407
17.65	0.375	0.365	0.40	0.380
18.92	0.355	0.34	0.38	0.358
20.19	0.335	0.32	0.36	0.338
21.46	0.315	0.30	0.34	0.318
22.73	0.30	0.285	0.32	0.302
24.0	0.28	0.27	0.305	0.285
25.27	0.265	0.25	0.29	0.268
26.54	0.245	0.235	0.27	0.250
27.81	0.22	0.210	0.25	0.227
29.08	0.13	0.17	0.21	0.170
30.35	0.10 —	0.08 —	0.10 —	0.093 Rest.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt% Fe_2O_3

DATE: DEC. 6/87

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.093Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.32	—
4.95	—	0.928	—
7.49	—	0.722	—
10.03	0.305	0.595	0.608
11.3	0.284	0.552	0.619
12.57	0.265	0.505	0.643
13.84	0.247	0.467	0.660
15.11	0.230	0.433	0.676
16.38	0.214	0.407	0.682
17.65	0.199	0.380	0.693
18.92	0.186	0.358	0.702
20.19	0.174	0.338	0.710
21.46	0.164	0.318	0.729
22.73	0.154	0.302	0.737
24.0	0.146	0.285	0.760
25.27	0.139	0.268	0.794
26.54	—	0.250	—
27.81	—	0.227	—
29.08	—	0.170	—

wide - 0.692 ± 0.042

narrow - 0.693 ± 0.013

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

DATE: DEC. 8/87

Additions made to sample:

100g as-received + 4.57g SiO_2 + 5.23 g CaO

Atm.: H.P. Ar (gettered).

Total wt. of sample: 109.80g

Total wt. w/crucible: init.- 159.91 g

finl.- 159.58g

RUN#: 1

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	136	0.0	4.35
3	97	4.95	1.5
3	77	7.49	1.1
1	57	10.03	0.93
1	47	11.3	0.82
1	37	12.57	0.76
1	27	13.84	0.71
1	17	15.11	0.655
1	07	16.38	0.605
1	997	17.65	0.565
1	987	18.92	0.53
1	977	20.19	0.50
1	967	21.46	0.47
1	957	22.73	0.44
1	947	24.0	0.415
1	937	25.27	0.39
1	927	26.54	0.365
1	917	27.81	0.34
1	907	29.08	0.30
.3	~897	30.35	0.07 — BOTTOM.
		Depth = 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

DATE: DEC. 8/87

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.07 Ω RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	4.35	———
4.95	———	1.5	———
7.49	———	1.1	———
10.03	0.305	0.93	0.355
11.3	0.284	0.82	0.379
12.57	0.265	0.76	0.384
13.84	0.247	0.71	0.386
15.11	0.230	0.655	0.393
16.38	0.214	0.605	0.400
17.65	0.199	0.565	0.402
18.92	0.186	0.53	0.404
20.19	0.174	0.50	0.405
21.46	0.164	0.47	0.410
22.73	0.154	0.44	0.416
24.0	0.146	0.415	0.423
25.27	0.139	0.39	0.434
26.54	———	0.365	———
27.81	———	0.34	———
29.08	———	0.30	———

wide - 0.400 ± 0.014

narrow - 0.401 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

DATE: DEC. 8/87

Additions made to sample:

Atm.: H.P. Ar (gettered).

100g as-received + 4.57g SiO_2 + 5.23g CaO

Total wt. of sample: 109.80g

Total wt. w/crucible: init. - 159.91g.

finl. - 159.58g

RUN#: 2

TEMPERATURE: 1250°c ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	134	0.0	3.65
3	95	4.95	1.45
3	75	7.49	1.1
1	55	10.03	0.905
1	45	11.3	0.825
1	35	12.57	0.755
1	25	13.84	0.69
1	15	15.11	0.645
1	05	16.38	0.60
1	995	17.65	0.56
1	985	18.92	0.525
1	975	20.19	0.49
1	965	21.46	0.46
1	955	22.73	0.435
1	945	24.0	0.41
1	935	25.27	0.395
1	925	26.54	0.365
1	915	27.81	0.34
1	905	29.08	0.29
1	895	30.35	0.07 BOTTOM
		Depth. 30.35mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.07 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	3.65	———
4.95	———	1.45	———
7.49	———	1.1	———
10.03	0.305	0.905	0.365
11.3	0.284	0.825	0.376
12.57	0.265	0.755	0.387
13.84	0.247	0.69	0.398
15.11	0.230	0.645	0.400
16.38	0.214	0.60	0.404
17.65	0.199	0.56	0.406
18.92	0.186	0.525	0.409
20.19	0.174	0.49	0.414
21.46	0.164	0.46	0.421
22.73	0.154	0.435	0.422
24.0	0.146	0.41	0.429
25.27	0.139	0.395	0.428
26.54	———	0.365	———
27.81	———	0.34	———
29.08	———	0.29	———

wide – 0.406 ± 0.016

narrow – 0.407 ± 0.005

SLAG CONDUCTIVITY DETERMINATION X

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

DATE: DEC. 8/87

Additions made to sample:

100g as-received + 4.57g SiO_2 + 5.23g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 109.80g

Total wt. w/crucible: init.- 159.91g

finl.- 159.58g

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	134	0.0	3.8
3	95	4.95	1.5
3	75	7.49	1.125
1	55	10.03	0.92
1	45	11.3	0.84
1	35	12.57	0.77
1	25	13.84	0.71
1	15	15.11	0.66
1	05	16.38	0.61
1	995	17.65	0.57
1	985	18.92	0.54
1	975	20.19	0.50
1	965	21.46	0.475
1	955	22.73	0.45
1	945	24.0	0.42
1	935	25.27	0.40
1	925	26.54	0.37
1	915	27.81	0.345
1	905	29.08	0.30
1	895	30.35	0.08 BOTTOM
		Depth. 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.07 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	——	3.8	——
4.95	——	1.5	——
7.49	——	1.125	——
10.03	0.305	0.92	0.359
11.3	0.284	0.84	0.369
12.57	0.265	0.77	0.379
13.84	0.247	0.71	0.386
15.11	0.230	0.66	0.390
16.38	0.214	0.61	0.396
17.65	0.199	0.57	0.398
18.92	0.186	0.54	0.396
20.19	0.174	0.50	0.405
21.46	0.164	0.475	0.405
22.73	0.154	0.45	0.405
24.0	0.146	0.42	0.417
25.27	0.139	0.40	0.421
26.54	——	0.37	——
27.81	——	0.345	——
29.08	——	0.30	——

wide – 0.395 ± 0.014

narrow – 0.397 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

DATE: DEC. 8/87

Atm.: H.P. Ar (gettered).

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	4.35	3.65	3.8	3.93
4.95	1.5	1.45	1.5	1.483
7.49	1.1	1.1	1.125	1.108
10.03	0.93	0.905	0.92	0.918
11.3	0.82	0.825	0.84	0.828
12.57	0.76	0.755	0.77	0.762
13.84	0.71	0.69	0.71	0.703
15.11	0.655	0.645	0.66	0.653
16.38	0.605	0.60	0.61	0.605
17.65	0.565	0.56	0.57	0.565
18.92	0.53	0.525	0.54	0.532
20.19	0.50	0.49	0.50	0.497
21.46	0.47	0.46	0.475	0.468
22.73	0.44	0.435	0.45	0.442
24.0	0.415	0.41	0.42	0.415
25.27	0.39	0.395	0.40	0.395
26.54	0.365	0.365	0.37	0.367
27.81	0.34	0.34	0.345	0.342
29.08	0.30	0.29	0.30	0.297
30.35	0.07	0.07	0.07	0.07 Ref.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.07 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.93	—
4.95	—	1.483	—
7.49	—	1.108	—
10.03	0.305	0.918	0.360
11.3	0.284	0.828	0.375
12.57	0.265	0.762	0.383
13.84	0.247	0.703	0.390
15.11	0.230	0.653	0.395
16.38	0.214	0.605	0.400
17.65	0.199	0.565	0.402
18.92	0.186	0.532	0.403
20.19	0.174	0.497	0.408
21.46	0.164	0.468	0.412
22.73	0.154	0.442	0.414
24.0	0.146	0.415	0.423
25.27	0.139	0.395	0.428
26.54	—	0.367	—
27.81	—	0.342	—
29.08	—	0.297	—

wide – 0.400 ± 0.014

narrow – 0.402 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

DATE: DEC. 8/87

Additions made to sample:

100 g as-received + 4.57 g SiO_2 + 5.23 g CaO

Atm.: H.P. Ar (gettered).

Total wt. of sample: 109.80 g

Total wt. w/crucible: init.- 159.91 g

finl.- 159.58 g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	133	0.0	3.0
3	94	4.95	1.175
1	74	7.49	0.93
1	54	10.03	0.76
1	44	11.3	0.70
1	34	12.57	0.64
1	24	13.84	0.59
1	14	15.11	0.55
1	04	16.38	0.51
1	994	17.65	0.48
1	984	18.92	0.45
1	974	20.19	0.42
1	964	21.46	0.40
1	954	22.73	0.38
1	944	24.0	0.355
1	934	25.27	0.335
1	924	26.54	0.315
1	914	27.81	0.285
1	904	29.08	0.25
1	~894 —	— 30.35 —	— 0.07 BOTTOM.
		Depth 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt% CaO

DATE: DEC. 8/87

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.07 Ω **RUN#:** 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.0	—
4.95	—	1.175	—
7.49	—	0.93	—
10.03	0.305	0.76	0.442
11.3	0.284	0.70	0.451
12.57	0.265	0.64	0.465
13.84	0.247	0.59	0.475
15.11	0.230	0.55	0.479
16.38	0.214	0.51	0.486
17.65	0.199	0.48	0.485
18.92	0.186	0.45	0.489
20.19	0.174	0.42	0.497
21.46	0.164	0.40	0.497
22.73	0.154	0.38	0.497
24.0	0.146	0.355	0.512
25.27	0.139	0.335	0.525
26.54	—	0.315	—
27.81	—	0.285	—
29.08	—	0.25	—

wide - 0.485 ± 0.017

narrow - 0.498 ± 0.008

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

DATE: DEC. 8/87

Additions made to sample:

100g as-received + 4.57g SiO_2 + 5.23g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 109.80g

Total wt. w/crucible: init.- 159.91g
finl.- 159.58g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	133	0.0	3.0
3	94	4.95	1.2
1	74	7.49	0.96
1	54	10.03	0.78
1	44	11.3	0.71
1	34	12.57	0.65
1	24	13.84	0.605
1	14	15.11	0.56
1	04	16.38	0.525
1	994	17.65	0.49
1	984	18.92	0.46
1	974	20.19	0.435
1	964	21.46	0.41
1	954	22.73	0.39
1	944	24.0	0.37
1	934	25.27	0.35
1	924	26.54	0.325
1	914	27.81	0.30
1	904	29.08	0.265
1	894	30.35	0.07 BOTTOM.
		Depth 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.07 Ω RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	3.0	———
4.95	———	1.2	———
7.49	———	0.96	———
10.03	0.305	0.78	0.430
11.3	0.284	0.71	0.444
12.57	0.265	0.65	0.457
13.84	0.247	0.605	0.462
15.11	0.230	0.56	0.469
16.38	0.214	0.525	0.470
17.65	0.199	0.49	0.474
18.92	0.186	0.46	0.477
20.19	0.174	0.435	0.477
21.46	0.164	0.41	0.482
22.73	0.154	0.39	0.481
24.0	0.146	0.37	0.487
25.27	0.139	0.35	0.496
26.54	———	0.325	———
27.81	———	0.30	———
29.08	———	0.265	———

wide - 0.471 ± 0.013

narrow - 0.481 ± 0.004

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

DATE: DEC. 8/87

Additions made to sample:

100 g as-received + 4.57 g SiO_2 + 5.23 g CaO

Atm.: H.P. Ar (gettered).

Total wt. of sample: 109.80 g

Total wt. w/crucible: init.- 159.91 g

finl.- 159.58 g

RUN#: 3

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	133	0.0	2.5
3	94	4.95	1.075
1	74	7.49	0.91
1	54	10.03	0.74
1	44	11.3	0.665
1	34	12.57	0.61
1	24	13.84	0.56
1	14	15.11	0.52
1	04	16.38	0.48
1	994	17.65	0.445
1	984	18.92	0.415
1	974	20.19	0.39
1	964	21.46	0.365
1	954	22.73	0.34
1	944	24.0	0.32
1	934	25.27	0.30
1	924	26.54	0.28
1	914	27.81	0.26
1	904	29.08	0.22
1	894	30.35	0.07 BOTTOM
		Depth. 30.35 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

Atm.: H.P. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.07Ω RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.5	———
4.95	———	1.075	———
7.49	———	0.91	———
10.03	0.305	0.74	0.455
11.3	0.284	0.665	0.477
12.57	0.265	0.61	0.491
13.84	0.247	0.56	0.504
15.11	0.230	0.52	0.511
16.38	0.214	0.48	0.522
17.65	0.199	0.445	0.530
18.92	0.186	0.415	0.539
20.19	0.174	0.39	0.544
21.46	0.164	0.365	0.556
22.73	0.154	0.34	0.570
24.0	0.146	0.32	0.584
25.27	0.139	0.30	0.604
26.54	———	0.28	———
27.81	———	0.26	———
29.08	———	0.22	———

wide – 0.530 ± 0.033

narrow – 0.559 ± 0.019

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 8/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#1+2 only)
	RUN# 1	RUN# 2	RUN# 3	
0.0	3.0	3.0	2.5	3.0
4.95	1.175	1.2	1.075	1.188
7.49	0.93	0.96	0.91	0.945
10.03	0.76	0.78	0.74	0.770
11.3	0.70	0.71	0.665	0.705
12.57	0.64	0.65	0.61	0.645
13.84	0.59	0.605	0.56	0.598
15.11	0.55	0.56	0.52	0.555
16.38	0.51	0.525	0.48	0.518
17.65	0.48	0.49	0.445	0.485
18.92	0.45	0.46	0.415	0.455
20.19	0.42	0.435	0.39	0.428
21.46	0.40	0.41	0.365	0.405
22.73	0.38	0.39	0.34	0.385
24.0	0.355	0.37	0.32	0.363
25.27	0.335	0.35	0.30	0.343
26.54	0.315	0.325	0.28	0.320
27.81	0.285	0.30	0.26	0.293
29.08	0.25	0.265	0.22	0.258
30.35	— 0.07 —	0.07 —	— 0.07 —	— 0.07 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1300 °C ± 5°

$r_{ext.}$ = 0.07 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (1+2).	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	3.0	———
4.95	———	1.188	———
7.49	———	0.945	———
10.03	0.305	0.770	0.436
11.3	0.284	0.705	0.447
12.57	0.265	0.645	0.461
13.84	0.247	0.598	0.468
15.11	0.230	0.555	0.474
16.38	0.214	0.518	0.478
17.65	0.199	0.485	0.479
18.92	0.186	0.455	0.483
20.19	0.174	0.428	0.486
21.46	0.164	0.405	0.489
22.73	0.154	0.385	0.489
24.0	0.146	0.363	0.498
25.27	0.139	0.343	0.509.
26.54	———	0.320	———
27.81	———	0.293	———
29.08	———	0.258	———

wide – 0.477 ± 0.014

narrow – 0.489 ± 0.006 .

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 8/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar.

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5wt.% CaO

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			
	RUN# 1	RUN# 2	RUN# 3	AVG.
0.0	3.0	3.0	2.5	2.83
4.95	1.175	1.2	1.075	1.15
7.49	0.93	0.96	0.91	0.933
10.03	0.76	0.78	0.74	0.760
11.3	0.70	0.71	0.665	0.692
12.57	0.64	0.65	0.61	0.633
13.84	0.59	0.605	0.56	0.585
15.11	0.55	0.56	0.52	0.543
16.38	0.51	0.525	0.48	0.505
17.65	0.48	0.49	0.445	0.472
18.92	0.45	0.46	0.415	0.442
20.19	0.42	0.435	0.39	0.415
21.46	0.40	0.41	0.365	0.392
22.73	0.38	0.39	0.34	0.370
24.0	0.355	0.37	0.32	0.348
25.27	0.335	0.35	0.30	0.328
26.54	0.315	0.325	0.28	0.307
27.81	0.285	0.30	0.26	0.282
29.08	0.25	0.265	0.22	0.245
30.35	0.07	0.07	0.07	0.07 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO2 with 5wt.% CaO.

DATE: DEC. 8/87

Atm.: H.P. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.07 Ω

DEPTH (mm)	CELL CONSTANT (cm⁻¹)	RESISTANCE (ohm)	CONDUCTIVITY (ohm⁻¹.cm⁻¹)
0.0	—	2.83	—
4.95	—	1.15	—
7.49	—	0.933	—
10.03	0.305	0.760	0.442
11.3	0.284	0.692	0.457
12.57	0.265	0.633	0.471
13.84	0.247	0.585	0.480
15.11	0.230	0.543	0.486
16.38	0.214	0.505	0.492
17.65	0.199	0.472	0.495
18.92	0.186	0.442	0.500
20.19	0.174	0.415	0.504
21.46	0.164	0.392	0.509
22.73	0.154	0.370	0.513
24.0	0.146	0.348	0.525
25.27	0.139	0.328	0.539
26.54	—	0.307	—
27.81	—	0.282	—
29.08	—	0.245	—

wide – ~~0.400 ± 0.014~~ 0.494 ± 0.020

narrow – ~~0.402 ±~~ 0.510 ± 0.010

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO addition   DATE: DEC. 20/87

Additions made to sample:

90 g as-received + 4.11 g SiO_2 + 9.0 g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.11 g

Total wt. w/crucible: init.- 152.47

finl.- 151.54

RUN#: 1   TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	104	0.0	2.9
3	65	4.95	1.15
1	45	7.49	0.94
1	25	10.03	0.78
1	15	11.3	0.715
1	05	12.57	0.665
1	995	13.84	0.62
1	985	15.11	0.58
1	975	16.38	0.545
1	965	17.65	0.51
1	955	18.92	0.48
1	945	20.19	0.455
1	935	21.46	0.43
1	925	22.73	0.40
1	915	24.0	0.38
1	905	25.27	0.355
1	895	26.54	0.325
1	885	27.81	0.245
1	879	BOTTOM ~~29.08~~	ε 0.06
		Depth. 28.6 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

DATE: DEC. 20/87

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1} \cdot cm^{-1}$)
0.0	——	2.9	——
4.95	——	1.15	——
7.49	——	0.94	——
10.03	0.305	0.78	0.424
11.3	0.284	0.715	0.434
12.57	0.265	0.665	0.438
13.84	0.247	0.62	0.441
15.11	0.230	0.58	0.442
16.38	0.214	0.545	0.441
17.65	0.199	0.51	0.442
18.92	0.186	0.48	0.443
20.19	0.174	0.455	0.441
21.46	0.164	0.43	0.443
22.73	0.154	0.40	0.453
24.0	0.146	0.38	0.456
25.27	0.139	0.355	0.471
26.54	——	0.325	——
27.81	——	0.245	——
29.08	——	——	——

wide – 0.443 ± 0.006

narrow – 0.442 ± 0.0008

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

DATE: DEC. 20/87

Additions made to sample:

90g as-received + 4.11g SiO_2 + 9.0g CaO

Atm.: A.P. Ar (gettered)

Total wt. of sample: 103.11g

Total wt. w/crucible: init.- 152.47g
finl.- 151.54g

RUN#: 2

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	105	0.0	3.0
3	66	4.95	1.2
1	46	7.49	0.95
1	26	10.03	~~76~~ 0.77
1	16	11.3	0.70
1	06	12.57	0.64
1	996	13.84	0.60
1	986	15.11	0.56
1	976	16.38	0.52
1	966	17.65	0.50
1	956	18.92	0.46
1	946	20.19	0.44
1	936	21.46	0.415
1	926	22.73	0.385
1	916	24.0	0.36
1	906	25.27	0.34
1	896	26.54	0.305
1 (0.3)	886	27.81	0.25 (0.285)
1	876	BOTTOM ~~29.08~~	0.06
		Depth. 29.08 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 20/87

Atm.: H.P. Ar

$r_{ext.}$ = 0.06Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.0	—
4.95	—	1.2	—
7.49	—	0.95	—
10.03	0.305	0.77	0.430
11.3	0.284	0.70	0.444
12.57	0.265	0.64	0.457
13.84	0.247	0.60	0.457
15.11	0.230	0.56	0.460
16.38	0.214	0.52	0.465
17.65	0.199	0.50	0.452
18.92	0.186	0.46	0.465
20.19	0.174	0.44	0.447
21.46	0.164	0.415	0.462
22.73	0.154	0.385	0.474
24.0	0.146	0.36	0.487
25.27	0.139	0.34	0.496
26.54	—	0.305	—
27.81	—	0.25	—
29.08	—	—	—

wide – 0.461 ± 0.012

narrow – 0.458 ± 0.008

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO

DATE: DEC. 20/87

Additions made to sample:

90 g as-received + 4.11 g SiO_2 + 9.0 g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.11 g

Total wt. w/crucible: init.- 152.47 g
finl.- 151.54

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	104	0.0	3.4
3	65	4.95	1.25
3	45	7.49	1.0
1	25	10.03	0.82
1	15	11.3	0.755
1	05	12.57	0.70
1	995	13.84	0.65
1	985	15.11	0.60
1	975	16.38	0.56
1	965	17.65	0.53
1	955	18.92	0.50
1	945	20.19	0.47
1	935	21.46	0.445
1	925	22.73	0.42
1	915	24.0	0.40
1	905	25.27	0.37
1	895	26.54	0.34
1	885	27.81	0.28
1	878	BOTTOM ~~29.08~~	0.06
		Depth. 28.7 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO.

DATE: DEC. 20/87

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	3.4	———
4.95	———	1.25	———
7.49	———	1.0	———
10.03	0.305	0.82	0.401
11.3	0.284	0.755	0.409
12.57	0.265	0.70	0.414
13.84	0.247	0.65	0.419
15.11	0.230	0.60	0.426
16.38	0.214	0.56	0.428
17.65	0.199	0.53	0.423
18.92	0.186	0.50	0.423
20.19	0.174	0.47	0.424
21.46	0.164	0.445	0.426
22.73	0.154	0.42	0.428
24.0	0.146	0.40	0.429
25.27	0.139	0.37	0.448
26.54	———	0.34	———
27.81	———	0.28	———
29.08	———	———	———

wide – 0.423 ± 0.006

narrow – 0.425 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 20/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: U.P. Ar (gettered)

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.9	3.0	3.4	3.10
4.95	1.15	1.2	1.25	1.20
7.49	0.94	0.95	1.0	0.963
10.03	0.78	0.77	0.82	0.790
11.3	0.715	0.70	0.755	0.723
12.57	0.665	0.64	0.70	0.668
13.84	0.62	0.60	0.65	0.623
15.11	0.58	0.56	0.60	0.580
16.38	0.545	0.52	0.56	0.542
17.65	0.51	0.50	0.53	0.513
18.92	0.48	0.46	0.50	0.480
20.19	0.455	0.44	0.47	0.455
21.46	0.43	0.415	0.445	0.430
22.73	0.40	0.385	0.42	0.402
24.0	0.38	0.36	0.40	0.380
25.27	0.355	0.34	0.37	0.355
26.54	0.325	0.305	0.34	0.323
27.81	0.245	0.25	0.28	0.258
~~29.08~~	Rext. 0.06	Rext. 0.06	Rext. 0.06	0.06

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 20/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO addition.

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	3.10	—
4.95	—	1.20	—
7.49	—	0.963	—
10.03	0.305	0.790	0.418
11.3	0.284	0.723	0.428
12.57	0.265	0.668	0.436
13.84	0.247	0.623	0.439
15.11	0.230	0.580	0.442
16.38	0.214	0.542	0.444
17.65	0.199	0.513	0.439
18.92	0.186	0.480	0.443
20.19	0.174	0.455	0.441
21.46	0.164	0.430	0.443
22.73	0.154	0.402	0.450
24.0	0.146	0.380	0.456
25.27	0.139	0.355	0.471
26.54	—	0.323	—
27.81	—	0.258	—
29.08	—	—	—

wide – 0.442 ± 0.007

narrow – 0.442 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10wt.% CaO

DATE: DEC. 20/87

Additions made to sample:

90g as-received + 4.11g SiO_2 + 9.0g CaO

Atm.: A.P. Ar (gettered).

Total wt. of sample: 103.11g

Total wt. w/crucible: init.- 152.47g
finl.- 151.54

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	103	0.0	2.45
1	64	4.95	1.0
1	44	7.49	0.75
1	24	10.03	0.61
1	14	11.3	0.56
1	04	12.57	0.505
1	994	13.84	0.475
1	984	15.11	0.44
1	974	16.38	0.41
1	964	17.65	0.39
1	954	18.92	0.36
1	944	20.19	0.34
1	934	21.46	0.32
1	924	22.73	0.29
1	914	24.0	0.30
1	904	25.27	0.28
1	894	26.54	0.255
1 (0.3)	884	27.81	0.155 (0.20)
1 (0.3)	878	BOTTOM ~~29.08~~	0.02 (0.06)
		Depth. 28.6 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

DATE: DEC.20/87

Atm.: HP.Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.02 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.45	—
4.95	—	1.0	—
7.49	—	0.75	—
10.03	0.305	0.61	0.517
11.3	0.284	0.56	0.526
12.57	0.265	0.505	0.546
13.84	0.247	0.475	0.543
15.11	0.230	0.44	0.548
16.38	0.214	0.41	0.549
17.65	0.199	0.39	0.538
18.92	0.186	0.36	0.547
20.19	0.174	0.34	0.544
21.46	0.164	0.32	0.547
22.73	0.154	0.29	0.570
24.0	0.146	0.30	0.521
25.27	0.139	0.28	0.535
26.54	—	0.255	—
27.81	—	0.155	—
29.08	—	—	—

wide – 0.544 ± 0.013

narrow – 0.546 ± 0.0017

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO

DATE: DEC. 20/87

Additions made to sample:

90 g as-received + 4.11 g SiO_2 + 9.0 g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.11 g

Total wt. w/crucible: init. - 152.47 g
finl. - 151.54

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	103	0.0	2.65
3	64	4.95	0.95
1	44	7.49	0.78
1	24	10.03	0.65
1	14	11.3	0.60
1	04	12.57	0.55
1	994	13.84	0.50
1	984	15.11	0.48
1	974	16.38	0.45
1	964	17.65	0.42
1	954	18.92	0.40
1	944	20.19	0.38
1	934	21.46	0.355
1	924	22.73	0.33
1	914	24.0	0.315
1	904	25.27	0.29
1	894	26.54	0.27
1	884	27.81	0.20
1 (0.3)	878 BOTTOM	~~29.08~~	0.025 (0.06)
		Depth. 28.6 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 20/87

Atm.: HP. Ar

$r_{ext.}$ = 0.025Ω RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.65	———
4.95	———	0.95	———
7.49	———	0.78	———
10.03	0.305	0.65	0.488
11.3	0.284	0.60	0.494
12.57	0.265	0.55	0.505
13.84	0.247	0.50	0.520
15.11	0.230	0.48	0.505
16.38	0.214	0.45	0.504
17.65	0.199	0.42	0.504
18.92	0.186	0.40	0.496
20.19	0.174	0.38	0.490
21.46	0.164	0.355	0.497
22.73	0.154	0.33	0.505
24.0	0.146	0.315	0.503
25.27	0.139	0.29	0.525
26.54	———	0.27	———
27.81	———	0.20	———
29.08	———	———	———

wide - 0.502 ± 0.008

narrow - 0.498 ± 0.006

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO

DATE: DEC. 20/87

Additions made to sample:

90g as-received + 4.11g SiO_2 + 9.0g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.11g

Total wt. w/crucible: init.- 152.47g
finl.- 151.54g

RUN#: 3

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	103	0.0	2.8
3	64	4.95	1.0
1	44	7.49	0.83
1	24	10.03	0.69
1	14	11.3	0.625
1	04	12.57	0.585
1	994	13.84	0.54
1	984	15.11	0.505
1	974	16.38	0.475
1	964	17.65	0.45
1	954	18.92	0.43
1	944	20.19	0.40
1	934	21.46	0.38
1	924	22.73	0.365
1	914	24.0	0.34
1	904	25.27	0.32
1	894	26.54	0.30
1	884	27.81	0.235
1 (0.3	878	29.08	0.05 (0.06)
		Depth. 28.6 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 20/87

Atm.: H.P. Ar

$r_{ext.}$ = 0.05Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.8	—
4.95	—	1.0	—
7.49	—	0.83	—
10.03	0.305	0.69	0.477
11.3	0.284	0.625	0.494
12.57	0.265	0.585	0.495
13.84	0.247	0.54	0.504
15.11	0.230	0.505	0.505
16.38	0.214	0.475	0.504
17.65	0.199	0.45	0.498
18.92	0.186	0.43	0.489
20.19	0.174	0.40	0.497
21.46	0.164	0.38	0.497
22.73	0.154	0.365	0.489
24.0	0.146	0.34	0.503
25.27	0.139	0.32	0.515
26.54	—	0.30	—
27.81	—	0.235	—
29.08	—	—	—

wide – 0.498 ± 0.006

narrow – 0.495 ± 0.006

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 20/87 X

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#2+3)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.45	2.65	2.8	2.725
4.95	1.0	0.95	1.0	0.975
7.49	0.75	0.78	0.83	0.805
10.03	0.61	0.65	0.69	0.670
11.3	0.56	0.60	0.625	0.613
12.57	0.505	0.55	0.585	0.568
13.84	0.475	0.50	0.54	0.520
15.11	0.44	0.48	0.505	0.493
16.38	0.41	0.45	0.475	~~0.463~~ 0.463
17.65	0.39	0.42	0.45	0.435
18.92	0.36	0.40	0.43	0.415
20.19	0.34	0.38	0.40	0.390
21.46	0.32	0.355	0.38	0.368
22.73	0.29	0.33	0.365	0.348
24.0	0.30	0.315	0.34	0.328
25.27	0.28	0.29	0.32	0.305
26.54	0.255	0.27	0.30	0.285
27.81	0.155	0.20	0.235	0.218
29.08	Rext 0.02 —	Rext 0.025 —	Rext. 0.05 —	0.0375 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 20/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.0375 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (2+3) only	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.725	—
4.95	—	0.975	—
7.49	—	0.805	—
10.03	0.305	0.670	0.482
11.3	0.284	0.613	0.493
12.57	0.265	0.568	~~0.4~~ 0.500
13.84	0.247	0.520	0.512
15.11	0.230	0.493	0.505
16.38	0.214	0.463	0.503
17.65	0.199	0.435	0.501
18.92	0.186	0.415	0.493
20.19	0.174	0.390	0.494
21.46	0.164	0.368	0.496
22.73	0.154	0.348	0.496
24.0	0.146	0.328	0.503
25.27	0.139	0.305	0.520
26.54	—	0.285	—
27.81	—	0.218	—
29.08	—	—	—

wide. – 0.500 ± 0.006

narrow – 0.496 ± 0.004.

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 20/87

Atm.: HP. Ar.

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.45	2.65	2.8	2.633
4.95	1.0	0.95	1.0	0.983
7.49	0.75	0.78	0.83	0.787
10.03	0.61	0.65	0.69	0.650
11.3	0.56	0.60	0.625	0.595
12.57	0.505	0.55	0.585	0.547
13.84	0.475	0.50	0.54	0.505
15.11	0.44	0.48	0.505	0.475
16.38	0.41	0.45	0.475	0.445
17.65	0.39	0.42	0.45	0.420
18.92	0.36	0.40	0.43	0.397
20.19	0.34	0.38	0.40	0.373
21.46	0.32	0.355	0.38	0.352
22.73	0.29	0.33	0.365	0.328
24.0	0.30	0.315	0.34	0.318
25.27	0.28	0.29	0.32	0.297
26.54	0.255	0.27	0.30	0.275
27.81	0.155	0.20	0.235	0.197
29.08	Rext 0.02 —	Rext. 0.025 —	Rext. 0.05 —	0.032 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 20/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10% CaO

Atm.: HP. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.032 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	——	2.633	——
4.95	——	0.983	——
7.49	——	0.787	——
10.03	0.305	0.650	0.494
11.3	0.284	0.595	0.504
12.57	0.265	0.547	0.515
13.84	0.247	0.505	0.522
15.11	0.230	0.475	0.519
16.38	0.214	0.445	0.518
17.65	0.199	0.420	0.513
18.92	0.186	0.397	~~0.50~~ 0.510
20.19	0.174	0.373	0.510
21.46	0.164	0.352	0.513
22.73	0.154	0.328	0.520
24.0	0.146	0.318	0.510
25.27	0.139	0.297	0.525
26.54	——	0.275	——
27.81	——	0.197	——
29.08	——	——	——

wide – 0.514 ± 0.005

narrow – 0.513 ± 0.004

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO addition DATE: DEC. 21/87

Additions made to sample: Atm.: H.P. Ar (gettered)

90 g as-received + 4.11 g SiO_2 + 14.12 g CaO

Total wt. of sample: 108.23 g Total wt. w/crucible: init.- 155.38 g
fin.- 153.84 g

RUN#: 1 TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	121	0.0	2.85
3	82	4.95	1.175
1	62	7.49	0.955
1	42	10.03	0.79
1	32	11.3	0.72
1	22	12.57	0.67
1	12	13.84	0.62
1	02	15.11	0.58
1	992	16.38	0.545
1	982	17.65	0.51
1	972	18.92	0.48
1	962	20.19	0.46
1	952	21.46	0.43
1	942	22.73	0.41
1	932	24.0	0.39
1	922	25.27	0.365
1	912	26.54	0.34
1	902	27.81	0.30
1	892	29.08	0.11
1	886	BOTTOM.	0.04
		Depth 29.8 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.04 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.85	—
4.95	—	1.175	—
7.49	—	0.955	—
10.03	0.305	0.79	0.407
11.3	0.284	0.72	0.418
12.57	0.265	0.67	0.421
13.84	0.247	0.62	0.426
15.11	0.230	0.58	0.426
16.38	0.214	0.545	0.424
17.65	0.199	0.51	0.424
18.92	0.186	0.48	0.423
20.19	0.174	0.46	0.414
21.46	0.164	0.43	0.421
22.73	0.154	0.41	0.416
24.0	0.146	0.39	0.417
25.27	0.139	0.365	0.428
26.54	—	0.34	—
27.81	—	0.30	—
29.08	—	0.11	—

wide - 0.421 ± 0.004

narrow - 0.423 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO

DATE: DEC. 21/87

Additions made to sample:

90 g as-received + 4.11 g SiO_2 + 14.12 g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.23 g

Total wt. w/crucible: init.- 155.38 g
finl.- 153.84

RUN#: 2

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	120	0.0	3.0
3	81	4.95	1.2
1	61	7.49	0.98
1	41	10.03	0.80
1	31	11.3	0.735
1	21	12.57	0.68
1	11	13.84	0.635
1	01	15.11	0.59
1	991	16.38	0.555
1	981	17.65	0.525
1	971	18.92	0.49
1	961	20.19	0.46
1	951	21.46	0.44
1	941	22.73	0.42
1	931	24.0	0.40
1	921	25.27	0.37
1	911	26.54	0.34
1	901	27.81	0.305
1	891	29.08	0.045
1	886	BOTTOM.	0.04
		Depth 29.8 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO.

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.04 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1} \cdot cm^{-1}$)
0.0	——	3.0	——
4.95	——	1.2	——
7.49	——	0.98	——
10.03	0.305	0.80	0.401
11.3	0.284	0.735	0.409
12.57	0.265	0.68	0.414
13.84	0.247	0.635	0.415
15.11	0.230	0.59	0.418
16.38	0.214	0.555	0.416
17.65	0.199	0.525	0.410
18.92	0.186	0.49	0.413
20.19	0.174	0.46	0.414
21.46	0.164	0.44	0.410
22.73	0.154	0.42	0.405
24.0	0.146	0.40	0.406
25.27	0.139	0.37	0.421
26.54	——	0.34	——
27.81	——	0.305	——
29.08	——	0.045	——

wide – 0.412 ± 0.004

narrow – 0.414 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15wt.% CaO

DATE: DEC. 21/87

Additions made to sample:

90g as-received + 4.11g SiO_2 + 14.12g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.23g

Total wt. w/crucible: init.- 155.38g

finl.- 153.84

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
10	119	0.0	2.75
3	80	4.95	1.15
1	60	7.49	0.95
1	40	10.03	0.78
1	30	11.3	0.71
1	20	12.57	0.66
1	10	13.84	0.61
1	0	15.11	0.57
1	990	16.38	0.53
1	980	17.65	0.50
1	970	18.92	0.475
1	960	20.19	0.445
1	950	21.46	0.42
1	940	22.73	0.395
1	930	24.0	0.37
1	920	25.27	0.35
1	910	26.54	0.32
1	900	27.81	0.29
1	890	29.08	0.045
1	886	BOTTOM	0.04
		Depth. 29.6 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.04 Ω RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.75	—
4.95	—	1.15	—
7.49	—	0.95	—
10.03	0.305	0.78	0.412
11.3	0.284	0.71	0.424
12.57	0.265	0.66	0.427
13.84	0.247	0.61	0.433
15.11	0.230	0.57	0.433
16.38	0.214	0.53	0.437
17.65	0.199	0.50	0.433
18.92	0.186	0.475	0.423
20.19	0.174	0.445	0.430
21.46	0.164	0.42	0.432
22.73	0.154	0.395	0.434
24.0	0.146	0.37	0.442
25.27	0.139	0.35	0.448
26.54	—	0.32	—
27.81	—	0.29	—
29.08	—	0.045	—

wide – 0.432 ± 0.006

narrow – 0.431 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 21/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.85	3.0	2.75	2.867
4.95	1.175	1.2	1.15	1.175
7.49	0.955	0.98	0.95	0.962
10.03	0.79	0.80	0.78	0.790
11.3	0.72	0.735	0.71	0.722
12.57	0.67	0.68	0.66	0.670
13.84	0.62	0.635	0.61	0.622
15.11	0.58	0.59	0.57	0.580
16.38	0.545	0.555	0.53	0.543
17.65	0.51	0.525	0.50	0.512
18.92	0.48	0.49	0.475	0.482
20.19	0.46	0.46	0.445	0.455
21.46	0.43	0.44	0.42	0.430
22.73	0.41	0.42	0.395	0.408
24.0	0.39	0.40	0.37	0.387
25.27	0.365	0.37	0.35	0.362
26.54	0.34	0.34	0.32	0.333
27.81	0.30	0.305	0.29	0.298
29.08	0.11	0.045 <- ?	0.045	——
	Rext. 0.04	Rext. 0.04	Rext. 0.04	Rext. 0.04

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO

Atm.: H.P. Ar (Gettered)

TEMPERATURE: 1250°c ± 5°

$r_{ext.}$ = 0.04 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.867	—
4.95	—	1.175	—
7.49	—	0.962	—
10.03	0.305	0.790	0.407
11.3	0.284	0.722	0.416
12.57	0.265	0.670	0.421
13.84	0.247	0.622	0.424
15.11	0.230	0.580	0.426
16.38	0.214	0.543	0.425
17.65	0.199	0.512	0.422
18.92	0.186	0.482	0.421
20.19	0.174	0.455	0.419
21.46	0.164	0.430	0.421
22.73	0.154	0.408	0.418
24.0	0.146	0.387	0.421
25.27	0.139	0.362	0.432
26.54	—	0.333	—
27.81	—	0.298	—
29.08	—	—	—

wide - 0.421 ± 0.003

narrow - 0.423 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 • Fe/SiO_2 with 15wt% CaO

DATE: DEC. 21/87

Additions made to sample:

90g as-received + 4.11g SiO_2 + 14.12g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.23g

Total wt. w/crucible: init.- 155.38g

finl.- 153.84

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	120	0.0	2.9
3	81	4.95	0.95
1	61	7.49	0.80
1	41	10.03	0.655
1	31	11.3	0.595
1	21	12.57	0.55
1	11	13.84	0.515
1	01	15.11	0.485
1	991	16.38	0.45
1	981	17.65	0.425
1	971	18.92	0.40
1	961	20.19	0.38
1	951	21.46	0.36
1	941	22.73	0.34
1	931	24.0	0.32
1	921	25.27	0.30
1	911	26.54	0.28
1	901	27.81	0.255
1	891	29.08	0.14
1	886	BOTTOM	0.04
		Depth 29.7 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.04 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.9	—
4.95	—	0.95	—
7.49	—	0.80	—
10.03	0.305	0.655	0.496
11.3	0.284	0.595	0.512
12.57	0.265	0.55	0.520
13.84	0.247	0.515	0.520
15.11	0.230	0.485	0.517
16.38	0.214	0.45	0.522
17.65	0.199	0.425	0.517
18.92	0.186	0.40	0.517
20.19	0.174	0.38	0.512
21.46	0.164	0.36	0.513
22.73	0.154	0.34	0.513
24.0	0.146	0.32	0.521
25.27	0.139	0.30	0.535
26.54	—	0.28	—
27.81	—	0.255	—
29.08	—	0.14	—

wide – 0.517 ± 0.004

narrow – 0.515 ± 0.004

X

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO

DATE: DEC. 21/87

Additions made to sample:

90 g as-received + 4.11 g SiO_2 + 14.12 g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.23 g

Total wt. w/crucible: init.- 155.38 g
finl.- 153.84 g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	119	0.0	2.9
3	80	4.95	1.05
1	60	7.49	0.83
1	40	10.03	0.685
1	30	11.3	0.635
1	20	12.57	0.58
1	10	13.84	0.545
1	0	15.11	0.505
1	990	16.38	0.475
1	980	17.65	0.45
1	970	18.92	0.425
1	960	20.19	0.40
1	950	21.46	0.38
1	940	22.73	0.36
1	930	24.0	0.34
1	920	25.27	0.32
1	910	26.54	0.30
1	900	27.81	0.27
1	890	29.08	0.06
1	886.	BOTTOM	0.06
		Depth 29.6 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO

Atm.: H.P. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.9	———
4.95	———	1.05	———
7.49	———	0.83	———
10.03	0.305	0.685	0.488
11.3	0.284	0.635	0.494
12.57	0.265	0.58	0.510
13.84	0.247	0.545	0.509
15.11	0.230	0.505	0.517
16.38	0.214	0.475	0.516
17.65	0.199	0.45	0.510
18.92	0.186	0.425	0.510
20.19	0.174	0.40	0.512
21.46	0.164	0.38	0.513
22.73	0.154	0.36	0.513
24.0	0.146	0.34	0.521
25.27	0.139	0.32	0.535
26.54	———	0.30	———
27.81	———	0.27	———
29.08	———	0.06	———

wide - 0.511 ± 0.007

narrow - 0.514 ± 0.004

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15wt.% CaO

DATE: DEC. 21/87

Additions made to sample:

90g as-received + 4.11g SiO_2 + 14.12g CaO

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.23g

Total wt. w/crucible: init.- 155.38g
finl.- 153.84g

RUN#: 3

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	119	0.0	2.9
3	80	4.95	1.05
1	60	7.49	0.84
1	40	10.03	0.69
1	30	11.3	0.64
1	20	12.57	0.595
1	10	13.84	0.55
1	0	15.11	0.515
1	990	16.38	0.48
1	980	17.65	0.455
1	970	18.92	0.43
1	960	20.19	0.41
1	950	21.46	0.385
1	940	22.73	0.365
1	930	24.0	0.35
1	920	25.27	0.33
1	910	26.54	0.305
1	900	27.81	0.28
1	890	29.08	0.06
1	886	BOTTOM	Rest. 0.06
		Depth. 29.6 mm	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO

Atm.: H.P. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.9	———
4.95	———	1.05	———
7.49	———	0.84	———
10.03	0.305	0.69	0.484
11.3	0.284	0.64	0.490
12.57	0.265	0.595	0.495
13.84	0.247	0.55	0.504
15.11	0.230	0.515	0.505
16.38	0.214	0.48	0.510
17.65	0.199	0.455	0.504
18.92	0.186	0.43	0.503
20.19	0.174	0.41	0.497
21.46	0.164	0.385	0.505
22.73	0.154	0.365	0.505
24.0	0.146	0.35	0.503
25.27	0.139	0.33	0.515
26.54	———	0.305	———
27.81	———	0.28	———
29.08	———	0.06	———

wide – 0.502 ± 0.006

narrow – 0.503 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 21/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15wt.% CaO

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#2+3 only)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.9	2.9	2.9	2.90
4.95	0.95	1.05	1.05	1.05
7.49	0.80	0.83	0.84	0.835
10.03	0.655	0.685	0.69	0.688
11.3	0.595	0.635	0.64	0.638
12.57	0.55	0.58	0.595	0.588
13.84	0.515	0.545	0.55	0.548
15.11	0.485	0.505	0.515	0.510
16.38	0.45	0.475	0.48	0.478
17.65	0.425	0.45	0.455	0.453
18.92	0.40	0.425	0.43	0.428
20.19	0.38	0.40	0.41	0.405
21.46	0.36	0.38	0.385	0.383
22.73	0.34	0.36	0.365	0.363
24.0	0.32	0.34	0.35	0.345
25.27	0.30	0.32	0.33	0.325
26.54	0.28	0.30	0.305	0.303
27.81	0.255	0.27	0.28	0.275
29.08	0.14	0.06	0.06	—
	Rext. 0.04	Rext. 0.06	Rext. 0.06.	Rext. 0.06.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.9	—
4.95	—	1.05	—
7.49	—	0.835	—
10.03	0.305	0.688	0.486
11.3	0.284	0.638	0.491
12.57	0.265	0.588	0.502
13.84	0.247	0.548	0.506
15.11	0.230	0.510	0.511
16.38	0.214	0.478	0.512
17.65	0.199	0.453	0.506
18.92	0.186	0.428	0.505
20.19	0.174	0.405	0.504
21.46	0.164	0.383	0.508
22.73	0.154	0.363	0.508
24.0	0.146	0.345	0.512
25.27	0.139	0.325	0.525
26.54	—	0.303	—
27.81	—	0.275	—
29.08	—	—	—

wide – 0.506 ± 0.006

narrow – 0.507 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 21/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt. % CaO

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#1+2)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.9	2.9	2.9	2.90
4.95	0.95	1.05	1.05	1.00
7.49	0.80	0.83	0.84	0.815
10.03	0.655	0.685	0.69	0.670
11.3	0.595	0.635	0.64	0.615
12.57	0.55	0.58	0.595	0.565
13.84	0.515	0.545	0.55	0.530
15.11	0.485	0.505	0.515	0.495
16.38	0.45	0.475	0.48	0.463
17.65	0.425	0.45	0.455	0.438
18.92	0.40	0.425	0.43	0.413
20.19	0.38	0.40	0.41	0.390
21.46	0.36	0.38	0.385	0.370
22.73	0.34	0.36	0.365	0.350
24.0	0.32	0.34	0.35	0.330
25.27	0.30	0.32	0.33	0.310
26.54	0.28	0.30	0.305	0.290
27.81	0.255	0.27	0.28	0.263
29.08	0.14	0.06	0.06	—
	Rest. 0.04 —	Rest 0.06 —	Rest. 0.06 —	0.05 Rest.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION: DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15wt.% CaO Atm.: Hp. Ar

TEMPERATURE: 1300°C ± 5° $r_{ext.}$ = 0.05 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (1+2)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.90	———
4.95	———	1.00	———
7.49	———	0.815	———
10.03	0.305	0.670	0.492
11.3	0.284	0.615	0.503
12.57	0.265	0.565	0.515
13.84	0.247	0.530	~~0.514~~ 0.515
15.11	0.230	0.495	0.517
16.38	0.214	0.463	0.518
17.65	0.199	0.438	0.513
18.92	0.186	0.413	0.512
20.19	0.174	0.390	0.512
21.46	0.164	0.370	0.513
22.73	0.154	0.350	0.513
24.0	0.146	0.330	0.521
25.27	0.139	0.310	0.535
26.54	———	0.290	———
27.81	———	0.263	———
29.08	———	———	———

wide – 0.514 ± 0.005

narrow – 0.514 ± 0.004.

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 21/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar.

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15wt.% CaO

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.9	2.9	2.9	2.90
4.95	0.95	1.05	1.05	1.017
7.49	0.80	0.83	0.84	0.823
10.03	0.655	0.685	0.69	0.677
11.3	0.595	0.635	0.64	0.623
12.57	0.55	0.58	0.595	0.575
13.84	0.515	0.545	0.55	0.537
15.11	0.485	0.505	0.515	0.502
16.38	0.45	0.475	0.48	0.468
17.65	0.425	0.45	0.455	0.443
18.92	0.40	0.425	0.43	0.418
20.19	0.38	0.40	0.41	0.397
21.46	0.36	0.38	0.385	0.375
22.73	0.34	0.36	0.365	0.355
24.0	0.32	0.34	0.35	0.337
25.27	0.30	0.32	0.33	0.317
26.54	0.28	0.30	0.305	0.295
27.81	0.255	0.27	0.28	0.268
29.08	0.14	0.06	0.06	0.087
	Rext. 0.04	Rext. 0.06	Rext. 0.06	0.053 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15% CaO

Atm.: U.P. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.053Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.90	—
4.95	—	1.017	—
7.49	—	0.823	—
10.03	0.305	0.677	0.489
11.3	0.284	0.623	0.498
12.57	0.265	0.575	0.508
13.84	0.247	0.537	0.510
15.11	0.230	0.502	0.512
16.38	0.214	0.468	0.516
17.65	0.199	0.443	0.510
18.92	0.186	0.418	0.510
20.19	0.174	0.397	0.506
21.46	0.164	0.375	0.509
22.73	0.154	0.355	0.510
24.0	0.146	0.337	0.514
25.27	0.139	0.317	0.527
26.54	—	0.295	—
27.81	—	0.268	—
29.08	—	0.087	—

wide — 0.509 ± 0.004

narrow — 0.510 ± 0.003

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2

DATE: DEC. 9/87

Additions made to sample:

100g as-received + 0.13g SiO_2

Atm.: H.P. Ar (gettered).

Total wt. of sample: 100.13g

Total wt. w/crucible: init.- 147.53g
finl.- 147.49g

RUN#: 1

TEMPERATURE: ~~120~~ 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	106	0.0	2.15
1	67	4.95	0.98
1	47	7.49	0.77
1	27	10.03	0.63
1	17	11.3	0.575
1	07	12.57	0.53
1	997	13.84	0.495
1	987	15.11	0.46
1	977	16.38	0.43
1	967	17.65	0.405
1	957	18.92	0.38
1	947	20.19	0.36
1	937	21.46	0.34
1	927	22.73	0.32
1	917	24.0	0.29 ~~[illegible]~~
1 (0.3)	907	25.27	0.26 (0.29)
1 (0.3)	897	BOTTOM. 26.54	0.03 (0.065)
1 (0.3)	~~887~~	~~27.81~~	
		~~29.08~~	
		Depth. 26.5 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: H.P. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.15	—
4.95	—	0.98	—
7.49	—	0.77	—
10.03	0.305	0.63	0.508
11.3	0.284	0.575	0.521
12.57	0.265	0.53	0.530
13.84	0.247	0.495	0.531
15.11	0.230	0.46	0.535
16.38	0.214	0.43	0.535
17.65	0.199	0.405	0.531
18.92	0.186	0.38	0.531
20.19	0.174	0.36	0.527
21.46	0.164	0.34	0.529
22.73	0.154	0.32	0.531
24.0	0.146	0.29	0.562
25.27	0.139	0.26	0.604
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide – 0.530 ± 0.004

narrow – 0.533 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2

DATE: DEC. 9/87

Additions made to sample:

100 g as-received + 0.13 g SiO_2

Atm.: H.P. Ar (gettered).

Total wt. of sample: 100.13 g

Total wt. w/crucible: init.- 147.53 g

finl.- 147.49 g

RUN#: 2

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	111	0.0	2.8
3	72	4.95	0.96
1	52	7.49	0.81
1	32	10.03	0.65
1	22	11.3	0.60
1	12	12.57	0.55
1	02	13.84	0.51
1	992	15.11	0.48
1	982	16.38	0.45
1	972	17.65	0.425
1	962	18.92	0.40
1	952	20.19	0.37
1	942	21.46	0.35
1	932	22.73	0.325
1	922	24.0	0.30
1	912	25.27	0.275
1 (0.3)	902	~~26.54~~ BOTTOM	0.03 (0.065)
		27.81	
		29.08	
		Depth. 26.5 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: H.P. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1} \cdot cm^{-1}$)
0.0	—	2.8	—
4.95	—	0.96	—
7.49	—	0.81	—
10.03	0.305	0.65	0.492
11.3	0.284	0.60	0.498
12.57	0.265	0.55	0.510
13.84	0.247	0.51	0.515
15.11	0.230	0.48	0.511
16.38	0.214	0.45	0.510
17.65	0.199	0.425	0.504
18.92	0.186	0.40	0.503
20.19	0.174	0.37	0.512
21.46	0.164	0.35	0.513
22.73	0.154	0.325	0.522
24.0	0.146	0.30	0.541
25.27	0.139	0.275	0.567
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide – 0.513 ± 0.011

narrow – 0.509 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

X

SLAG SAMPLE: 0.95 Fe/SiO_2

DATE: DEC. 9/87

Additions made to sample:

100 g as-received + 0.13 g SiO_2

Atm.: H.P. Ar (Gettered).

Total wt. of sample: 100.13g

Total wt. w/crucible: init.- 147.53g

finl.- 147.49g

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	112	0.0	2.90
3	73	4.95	1.0
1	53	7.49	0.84
1	33	10.03	0.69
1	23	11.3	0.63
1	13	12.57	0.58
1	03	13.84	0.54
1	993	15.11	0.50
1	983	16.38	0.47
1	973	17.65	0.44
1	963	18.92	0.41
1	953	20.19	0.385
1	943	21.46	0.36
1	933	22.73	0.34
1	923	24.0	0.32
1	913	25.27	0.29
1	903 BOTTOM.	~~26.54~~	0.03
		27.81	
		29.08	
		Depth. 26.5 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: HP. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.90	———
4.95	———	1.0	———
7.49	———	0.84	———
10.03	0.305	0.69	0.462
11.3	0.284	0.63	0.473
12.57	0.265	0.58	0.482
13.84	0.247	0.54	0.484
15.11	0.230	0.50	0.489
16.38	0.214	0.47	0.486
17.65	0.199	0.44	0.486
18.92	0.186	0.41	0.489
20.19	0.174	0.385	0.490
21.46	0.164	0.36	0.497
22.73	0.154	0.34	0.497
24.0	0.146	0.32	0.503
25.27	0.139	0.29	0.535
26.54	———	———	———
27.81	———	———	———
29.08	———	———	———

wide – 0.489 ± 0.008

narrow – 0.487 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.95 Fe/SiO_2

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 9/87

Atm.: HP. Ar

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#2+3)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.15	2.8	2.90	2.85
4.95	0.98	0.96	1.0	0.980
7.49	0.77	0.81	0.84	0.825
10.03	0.63	0.65	0.69	0.670
11.3	0.575	0.60	0.63	0.615
12.57	0.53	0.55	0.58	0.565
13.84	0.495	0.51	0.54	0.525
15.11	0.46	0.48	0.50	0.490
16.38	0.43	0.45	0.47	0.460
17.65	0.405	0.425	0.44	0.433
18.92	0.38	0.40	0.41	0.405
20.19	0.36	0.37	0.385	0.378
21.46	0.34	0.35	0.36	0.355
22.73	0.32	0.325	0.34	0.333
24.0	0.29	0.30	0.32	0.310
25.27	0.26 (0.29)	0.275	0.29	0.283
26.54	0.03 (0.065)	0.03 (0.065)	0.03 —	0.03 Rept.
27.81				
29.08				

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: HP. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#2-3).	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.85	—
4.95	—	0.980	—
7.49	—	0.825	—
10.03	0.305	0.670	0.477
11.3	0.284	0.615	0.485
12.57	0.265	0.565	0.495
13.84	0.247	0.525	0.499
15.11	0.230	0.490	0.500
16.38	0.214	0.460	0.498
17.65	0.199	0.433	0.494
18.92	0.186	0.405	0.496
20.19	0.174	0.378	0.500
21.46	0.164	0.355	0.505
22.73	0.154	0.333	0.508
24.0	0.146	0.310	0.521
25.27	0.139	0.283	0.549.
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide - 0.500 ± 0.009

narrow - 0.497 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.95 Fe/SiO_2

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 9/87

Atm.: H.P. Ar (Gettered).

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.15	2.8	2.90	2.62
4.95	0.98	0.96	1.0	0.980
7.49	0.77	0.81	0.84	0.807
10.03	0.63	0.65	0.69	0.647
11.3	0.575	0.60	0.63	0.602
12.57	0.53	0.55	0.58	0.553
13.84	0.495	0.51	0.54	0.515
15.11	0.46	0.48	0.50	0.480
16.38	0.43	0.45	0.47	0.450
17.65	0.405	0.425	0.44	0.423
18.92	0.38	0.40	0.41	0.397
20.19	0.36	0.37	0.385	0.372
21.46	0.34	0.35	0.36	0.350
22.73	0.32	0.325	0.34	0.328
24.0	0.29	0.30	0.32	0.303
25.27	0.26 (0.29)	0.275	0.29	0.275
Bottom 26.54	0.03 (0.065) —	0.03 (0.065) →	0.03 —	0.03. Rext.
~~27.81~~				
~~29.08~~				

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: H.P. Ar (gettered).

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.03 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.62	—
4.95	—	0.980	—
7.49	—	0.807	—
10.03	0.305	0.647	0.494
11.3	0.284	0.602	0.497
12.57	0.265	0.553	0.507
13.84	0.247	0.515	0.509
15.11	0.230	0.480	0.511
16.38	0.214	0.450	0.510
17.65	0.199	0.423	0.506
18.92	0.186	0.397	0.507
20.19	0.174	0.372	0.509
21.46	0.164	0.350	0.513
22.73	0.154	0.328	0.517
24.0	0.146	0.303	0.535
25.27	0.139	0.275	0.567
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide – 0.511 ± 0.009

narrow – 0.509 ± 0.002

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO$_2$

DATE: DEC. 9/87

Additions made to sample:

100g as-received + 0.13g SiO$_2$

Atm.: H.P. Ar (gettered)

Total wt. of sample: 100.13g

Total wt. w/crucible: init.- 147.53g

finl.- 147.49g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	112	0.0	2.4
1	73	4.95	0.96
1	53	7.49	0.75
1	33	10.03	0.62
1	23	11.3	0.565
1	13	12.57	0.535
1	03	13.84	0.495
1	993	15.11	0.465
1	983	16.38	0.44
1	973	17.65	0.41
1	963	18.92	0.39
1	953	20.19	0.365
1	943	21.46	0.35
1	933	22.73	0.33
1	923	24.0	0.31
1	913	25.27	0.285
1	BOTTOM ~~903~~	~~26.54~~	0.08
		27.81	
		29.08	
		Depth. 26.5 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: HP. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.4	—
4.95	—	0.96	—
7.49	—	0.75	—
10.03	0.305	0.62	0.565
11.3	0.284	0.565	0.586
12.57	0.265	0.535	0.582
13.84	0.247	0.495	0.595
15.11	0.230	0.465	0.597
16.38	0.214	0.44	0.594
17.65	0.199	0.41	0.603
18.92	0.186	0.39	0.600
20.19	0.174	0.365	0.611
21.46	0.164	0.35	0.607
22.73	0.154	0.33	0.616
24.0	0.146	0.31	0.635
25.27	0.139	0.285	0.678
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide - 0.602 ± 0.015

narrow - 0.603 ± 0.007

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2

DATE: DEC. 9/87

Additions made to sample:

100 g as-received ± 0.13 g SiO_2

Atm.: H.P. Ar (Gettered)

Total wt. of sample: 100.13 g

Total wt. w/crucible: **init.**- 147.53 g
finl.- 147.49 g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	112	0.0	2.35
1	73	4.95	0.94
1	53	7.49	0.73
1	33	10.03	0.60
1	23	11.3	0.555
1	13	12.57	0.51
1	03	13.84	0.46
1	993	15.11	0.43
1	983	16.38	0.40
1	973	17.65	0.38
1	963	18.92	0.36
1	953	20.19	0.335
1	943	21.46	0.315
1	933	22.73	0.30
1	923	24.0	0.28
1	913	25.27	0.25
1	BOTTOM ~~903~~	26.54	0.04
		27.81	
		29.08	
		Depth. 26.5 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.04 Ω **RUN#:** 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.35	—
4.95	—	0.94	—
7.49	—	0.73	—
10.03	0.305	0.60	0.545
11.3	0.284	0.555	0.551
12.57	0.265	0.51	0.564
13.84	0.247	0.46	0.588
15.11	0.230	0.43	~~[illegible]~~ 0.590
16.38	0.214	0.40	0.594
17.65	0.199	0.38	0.585
18.92	0.186	0.36	0.581
20.19	0.174	0.335	0.590
21.46	0.164	0.315	0.596
22.73	0.154	0.30	0.592
24.0	0.146	0.28	0.608
25.27	0.139	0.25	0.662
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide - 0.585 ± 0.016

narrow - 0.589 ± 0.006

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2

DATE: DEC. 9/87

Additions made to sample:

100g as-received + 0.13g SiO_2

Atm.: H.P. Ar (gettered)

Total wt. of sample: 100.13g

Total wt. w/crucible: init.- 147.53g

finl.- 147.49g

RUN#: 3

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	112	0.0	2.35
1	73	4.95	0.94
1	53	7.49	0.725
1	33	10.03	0.585
1	23	11.3	0.54
1	13	12.57	0.495
1	03	13.84	0.46
1	993	15.11	0.43
1	983	16.38	0.40
1	973	17.65	0.37
1	963	18.92	0.35
1	953	20.19	0.325
1	943	21.46	0.31
1	933	22.73	0.295
1	923	24.0	0.275
1	913	25.27	0.25
1	BOTTOM.	26.54	0.04
		27.81	
		29.08	
		Depth 26.5 mm.	

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.04 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.35	—
4.95	—	0.94	—
7.49	—	0.725	—
10.03	0.305	0.585	0.560
11.3	0.284	0.54	0.568
12.57	0.265	0.495	0.582
13.84	0.247	0.46	0.588
15.11	0.230	0.43	0.590
16.38	0.214	0.40	0.594
17.65	0.199	0.37	0.603
18.92	0.186	0.35	0.600
20.19	0.174	0.325	0.611
21.46	0.164	0.31	0.607
22.73	0.154	0.295	0.604
24.0	0.146	0.275	0.621
25.27	0.139	0.25	0.662
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide - 0.597 ± 0.015

narrow - 0.603 ± 0.007

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.95 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 9/87

Atm.: H.P. Ar (gettered).

DEPTH (mm)	RESISTANCE (ohms)			AVG. (2+3 only)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.4	2.35	2.35	2.35
4.95	0.96	0.94	0.94	0.940
7.49	0.75	0.73	0.725	0.728
10.03	0.62	0.60	0.585	0.593
11.3	0.565	0.555	0.54	0.548
12.57	0.535	0.51	0.495	0.503
13.84	0.495	0.46	0.46	0.460
15.11	0.465	0.43	0.43	0.430
16.38	0.44	0.40	0.40	0.400
17.65	0.41	0.38	0.37	0.375
18.92	0.39	0.36	0.35	0.355
20.19	0.365	0.335	0.325	0.330
21.46	0.35	0.315	0.31	0.313
22.73	0.33	0.30	0.295	0.298
24.0	0.31	0.28	0.275	0.278
25.27	0.285	0.25	0.25	0.250
BOTTOM ~~26.54~~	0.08	0.04	0.04	0.04 R_{ext}.
27.81				
29.08				

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87.

SLAG SAMPLE: 0.95 Fe / SiO_2

Atm.: A.P. Ar (gettered)

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.04 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.35	—
4.95	—	0.940	—
7.49	—	0.728	—
10.03	0.305	0.593	0.552
11.3	0.284	0.548	0.559
12.57	0.265	0.503	0.572
13.84	0.247	0.460	0.588
15.11	0.230	0.430	0.590
16.38	0.214	0.400	0.594
17.65	0.199	0.375	0.594
18.92	0.186	0.355	0.590
20.19	0.174	0.330	0.600
21.46	0.164	0.313	0.601
22.73	0.154	0.298	0.597
24.0	0.146	0.278	0.613
25.27	0.139	0.250	0.662
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide - 0.591 ± 0.015

narrow - 0.596 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 9/87 X

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar.

SLAG SAMPLE: 0.95 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (1+3)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.4	2.35	2.35	2.375
4.95	0.96	0.94	0.94	0.950
7.49	0.75	0.73	0.725	0.738
10.03	0.62	0.60	0.585	0.603
11.3	0.565	0.555	0.54	0.553
12.57	0.535	0.51	0.495	0.515
13.84	0.495	0.46	0.46	0.478
15.11	0.465	0.43	0.43	0.448
16.38	0.44	0.40	0.40	0.420
17.65	0.41	0.38	0.37	0.390
18.92	0.39	0.36	0.35	0.370
20.19	0.365	0.335	0.325	0.345
21.46	0.35	0.315	0.31	0.330
22.73	0.33	0.30	0.295	0.313
24.0	0.31	0.28	0.275	0.293
25.27	0.285	0.25	0.25	0.268
~~26.54~~	0.08	0.04	0.04	0.06 Rest.
27.81				
29.08				

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (1+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.375	—
4.95	—	0.950	—
7.49	—	0.738	—
10.03	0.305	0.603	0.562
11.3	0.284	0.553	0.576
12.57	0.265	0.515	0.582
13.84	0.247	0.478	0.591
15.11	0.230	0.448	0.593
16.38	0.214	0.420	0.594
17.65	0.199	0.390	0.603
18.92	0.186	0.370	0.600
20.19	0.174	0.345	0.610
21.46	0.164	0.330	0.607
22.73	0.154	0.313	0.609
24.0	0.146	0.293	0.627
25.27	0.139	0.268	0.668
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide - 0.599 ± 0.014

narrow - 0.603 ± 0.006.

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 0.95 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 9/87

Atm.: H.P. Ar.

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.4	2.35	2.35	2.37
4.95	0.96	0.94	0.94	0.947
7.49	0.75	0.73	0.725	0.735
10.03	0.62	0.60	0.585	0.602
11.3	0.565	0.555	0.54	0.553
12.57	0.535	0.51	0.495	0.513
13.84	0.495	0.46	0.46	0.472
15.11	0.465	0.43	0.43	0.442
16.38	0.44	0.40	0.40	0.413
17.65	0.41	0.38	0.37	0.387
18.92	0.39	0.36	0.35	0.367
20.19	0.365	0.335	0.325	0.342
21.46	0.35	0.315	0.31	0.325
22.73	0.33	0.30	0.295	0.308
24.0	0.31	0.28	0.275	0.288
25.27	0.285	0.25	0.25	0.262
BOTTOM. 26.54	0.08	0.04	0.04	0.053 Red.
27.81				
29.08				

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2

Atm.: H.P. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.053 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.37	—
4.95	—	0.947	—
7.49	—	0.735	—
10.03	0.305	0.602	0.556
11.3	0.284	0.553	0.568
12.57	0.265	0.513	0.576
13.84	0.247	0.472	0.589
15.11	0.230	0.442	0.591
16.38	0.214	0.413	0.594
17.65	0.199	0.387	0.596
18.92	0.186	0.367	0.592
20.19	0.174	0.342	0.602
21.46	0.164	0.325	0.603
22.73	0.154	0.308	0.604
24.0	0.146	0.288	0.621
25.27	0.139	0.262	0.665
26.54	—	—	—
27.81	—	—	—
29.08	—	—	—

wide – 0.594 ± 0.014

narrow – 0.599 ± 0.005

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 11/87

Additions made to sample:

100g as-received + 0.13g SiO_2 + 5.0g Fe_2O_3

Atm.: H.P. Ar. (gettered.)

Total wt. of sample: 105.13g

Total wt. w/crucible: init.- 156.10g

finl.- 155.95g

RUN#: 1

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	95	0.0	1.9
1	56	4.95	0.86
1	36	7.49	0.665
1	16	10.03	0.545
1	06	11.3	0.50
1	996	12.57	0.46
1	986	13.84	0.435
1	976	15.11	0.40
1	966	16.38	0.375
1	956	17.65	0.345
1	946	18.92	0.32
1	936	20.19	0.30
1	926	21.46	0.275
1	916	22.73	0.255
1 (0.3)	906	24.0	0.23 (0.27)
1 (0.3)	896	25.27	0.20 (0.245)
1 (0.3)	886	26.54	0.165 (0.21)
1 (0.3)	876	27.81	0.08 (0.12)
1 (0.3)	872	~~29.08~~ BOTTOM	0.07 (0.115)
		Depth. 28.3 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: HP. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.07 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	1.9	———
4.95	———	0.86	———
7.49	———	0.665	———
10.03	0.305	0.545	0.642
11.3	0.284	0.50	0.660
12.57	0.265	0.46	0.679
13.84	0.247	0.435	0.677
15.11	0.230	0.40	0.697
16.38	0.214	0.375	0.702
17.65	0.199	0.345	0.724
18.92	0.186	0.32	0.744
20.19	0.174	0.30	0.757
21.46	0.164	0.275	0.800
22.73	0.154	0.255	0.832
24.0	0.146	0.23	0.913
25.27	0.139	0.20	1.069
26.54	———	0.165	———
27.81	———	0.08	———
29.08	———	———	———

wide – 0.744 ± 0.077

narrow – 0.709 ± 0.026

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3 DATE: DEC. 11/87

Additions made to sample:

100g as-received + 0.13g SiO_2 + 5.0g Fe_2O_3 Atm.: H.P. Ar (gettered)

Total wt. of sample: 105.13g Total wt. w/crucible: init.- 156.10g

finl.- 155.95g

RUN#: 2 TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	96	0.0	2.1
1	57	4.95	0.90
1	37	7.49	0.71
1	17	10.03	0.58
1	07	11.3	0.535
1	997	12.57	0.50
1	987	13.84	0.46
1	977	15.11	0.43
1	967	16.38	0.40
1	957	17.65	0.38
1	947	18.92	0.35
1	937	20.19	0.325
1	927	21.46	0.30
1	917	22.73	0.28
1	907	24.0	0.26
1	897	25.27	0.23
1	887	26.54	0.20
1	877	27.81	0.10
1	BOTTOM 874	29.08	0.08
		Depth. 28.2 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 11/87

Atm.: HP. Ar

$r_{ext.}$ = 0.08 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.1	———
4.95	———	0.90	———
7.49	———	0.71	———
10.03	0.305	0.58	0.610
11.3	0.284	0.535	0.624
12.57	0.265	0.50	0.631
13.84	0.247	0.46	0.650
15.11	0.230	0.43	0.657
16.38	0.214	0.40	0.669
17.65	0.199	0.38	0.663
18.92	0.186	0.35	~~0.688~~ 0.689
20.19	0.174	0.325	0.710
21.46	0.164	0.30	0.745
22.73	0.154	0.28	0.770
24.0	0.146	0.26	0.811
25.27	0.139	0.23	0.927
26.54	———	0.20	———
27.81	———	0.10	———
29.08	———	———	———

wide – 0.693 ± 0.060

narrow – 0.666 ± 0.015

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3 DATE: DEC. 11/87

Additions made to sample: Atm.: H.P. Ar (gettered)

100g as-received + 0.13g SiO_2 + 5.0g Fe_2O_3

Total wt. of sample: 105.13g Total wt. w/crucible: init. - 156.10g

finl. - 155.95g

RUN#: 3 TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	96	0.0	2.07
1	57	4.95	0.895
1	37	7.49	0.70
1	17	10.03	0.585
1	07	11.3	0.54
1	997	12.57	0.50
1	987	13.84	0.46
1	977	15.11	0.435
1	967	16.38	0.40
1	957	17.65	0.375
1	947	18.92	0.345
1	937	20.19	0.325
1	927	21.46	0.30
1	917	22.73	0.28
1	907	24.0	0.26
1	897	25.27	0.225
1	887	26.54	0.19
1	877	27.81	0.10
1	874	BOTTOM ~~29.00~~	0.08
		Depth. 28.2 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 11/87

Atm.: HP. Ar

$r_{ext.}$ = 0.08 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.07	—
4.95	—	0.895	—
7.49	—	0.70	—
10.03	0.305	0.585	0.604
11.3	0.284	0.54	0.617
12.57	0.265	0.50	0.631
13.84	0.247	0.46	0.650
15.11	0.230	0.435	0.648
16.38	0.214	0.40	0.669
17.65	0.199	0.375	0.675
18.92	0.186	0.345	0.702
20.19	0.174	0.325	0.710
21.46	0.164	0.30	0.745
22.73	0.154	0.28	0.770
24.0	0.146	0.26	0.811
25.27	0.139	0.225	0.959
26.54	—	0.19	—
27.81	—	0.10	—
29.08	—	—	—

wide – 0.693 ± 0.061

narrow – 0.669 ± 0.022

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

DATE: DEC. 11/87

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (2+3 only).
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.9	2.1	2.07	2.085
4.95	0.86	0.90	0.895	0.898
7.49	0.665	0.71	0.70	0.705
10.03	0.545	0.58	0.585	0.583
11.3	0.50	0.535	0.54	0.538
12.57	0.46	0.50	0.50	0.500
13.84	0.435	0.46	0.46	0.460
15.11	0.40	0.43	0.435	0.433
16.38	0.375	0.40	0.40	0.400
17.65	0.345	0.38	0.375	0.378
18.92	0.32	0.35	0.345	0.348
20.19	0.30	0.325	0.325	0.325
21.46	0.275	0.30	0.30	0.300
22.73	0.255	0.28	0.28	0.280
24.0	0.23	0.26	0.26	0.260
25.27	0.20	0.23	0.225	0.228
26.54	0.165	0.20	0.19	0.195
27.81	0.08	0.10	0.10	0.100
29.08		~~[illegible]~~		
BOTTOM.	Rext. 0.07.	Rext. 0.08	Rext. 0.08	Rext = 0.08.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.08 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.085	———
4.95	———	0.898	———
7.49	———	0.705	———
10.03	0.305	0.583	0.606
11.3	0.284	0.538	0.620
12.57	0.265	0.500	0.631
13.84	0.247	0.460	0.650
15.11	0.230	0.433	0.652
16.38	0.214	0.400	0.669
17.65	0.199	0.378	0.668
18.92	0.186	0.348	0.694
20.19	0.174	0.325	0.710
21.46	0.164	0.300	0.745
22.73	0.154	0.280	0.770
24.0	0.146	0.260	0.811
25.27	0.139	0.228	0.939
26.54	———	0.195	———
27.81	———	0.100	———
29.08	———	———	———

wide - 0.693 ± 0.061

narrow - 0.667 ± 0.018

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 11/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.9	2.1	2.07	2.023
4.95	0.86	0.90	0.895	0.885
7.49	0.665	0.71	0.70	0.692
10.03	0.545	0.58	0.585	0.570
11.3	0.50	0.535	0.54	0.525
12.57	0.46	0.50	0.50	0.487
13.84	0.435	0.46	0.46	0.452
15.11	0.40	0.43	0.435	0.422
16.38	0.375	0.40	0.40	0.392
17.65	0.345	0.38	0.375	0.367
18.92	0.32	0.35	0.345	0.338
20.19	0.30	0.325	0.325	0.317
21.46	0.275	0.30	0.30	0.292
22.73	0.255	0.28	0.28	0.272
24.0	0.23	0.26	0.26	0.25
25.27	0.20	0.23	0.225	0.218
26.54	0.165	0.20	0.19	0.185
27.81	0.08	0.10	0.10	———
29.08				
BOTTOM.	Rext. 0.07	Rext. 0.08	Rext. 0.08.	0.077 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5% Fe_2O_3

DATE: DEC. 11/87

Atm.: HP. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.077 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.023	—
4.95	—	0.885	—
7.49	—	0.692	—
10.03	0.305	0.570	0.619
11.3	0.284	0.525	0.634
12.57	0.265	0.487	0.646
13.84	0.247	0.452	0.659
15.11	0.230	0.422	0.667
16.38	0.214	0.392	0.679
17.65	0.199	0.367	0.686
18.92	0.186	0.338	0.713
20.19	0.174	0.317	0.725
21.46	0.164	0.292	0.763
22.73	0.154	0.272	0.790
24.0	0.146	0.25	0.844
25.27	0.139	0.218	0.986.
26.54	—	0.185	—
27.81	—	—	—
29.08	—	—	—

wide - 0.709 ± 0.066

narrow - 0.681 ± 0.021

X

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3

DATE: DEC. 11/87

Additions made to sample:

100g as-received + 0.13g SiO_2 + 5.0g Fe_2O_3

Atm.: H.P. Ar (Gettered)

Total wt. of sample: 105.13g

Total wt. w/crucible: init. - 156.10g

finl. - 155.95g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	99	0.0	1.85
1	60	4.95	0.78
1	40	7.49	0.61
1	20	10.03	0.51
1	10	11.3	0.465
1	~~9~~0	12.57	0.44
1	990	13.84	0.40
1	980	15.11	0.39
1	970	16.38	0.36
1	960	17.65	0.34
1	950	18.92	0.315
1	940	20.19	0.295
1	930	21.46	0.27
1	920	22.73	0.25
1	910	24.0	0.23
1	900	25.27	0.21
1	890	26.54	0.18
1	880	27.81	0.10
1	876	BOTTOM ~~29.08~~	Rext. = 0.08
		Depth. 28.3 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 11/87

Atm.: HP. Ar

$r_{ext.}$ = 0.08Ω RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.85	—
4.95	—	0.78	—
7.49	—	0.61	—
10.03	0.305	0.51	0.709
11.3	0.284	0.465	0.738
12.57	0.265	0.44	0.736
13.84	0.247	0.40	0.772
15.11	0.230	0.39	0.742
16.38	0.214	0.36	0.764
17.65	0.199	0.34	0.765
18.92	0.186	0.315	0.791
20.19	0.174	0.295	0.809
21.46	0.164	0.27	0.863
22.73	0.154	0.25	0.906
24.0	0.146	0.23	0.973
25.27	0.139	0.21	1.069
26.54	—	0.18	—
27.81	—	0.10	—
29.08	—	—	—

wide - 0.805 ± 0.077

narrow - 0.827 ± 0.057

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3

DATE: DEC. 11/87

Additions made to sample:

100g as-received + 0.13 g SiO_2 + 5.0 g Fe_2O_3

Atm.: H.P. Ar (gettered)

Total wt. of sample: 105.13g

Total wt. w/crucible: init.- 156.10g

finl.- 155.95g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	99	0.0	2.0
1	60	4.95	0.795
1	40	7.49	0.63
1	20	10.03	0.53
1	10	11.3	0.485
1	0	12.57	0.455
1	990	13.84	0.42
1	980	15.11	0.39
1	970	16.38	0.365
1	960	17.65	0.345
1	950	18.92	0.32
1	940	20.19	0.30
1	930	21.46	0.28
1	920	22.73	0.265
1	910	24.0	0.25
1	900	25.27	0.225
1	890	26.54	0.20
1	880	27.81	0.11
1	876	BOTTOM ~~29.08~~	Rext = 0.08
		Depth. 28.3 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.0	———
4.95	———	0.795	———
7.49	———	0.63	———
10.03	0.305	0.53	0.678
11.3	0.284	0.485	0.701
12.57	0.265	0.455	0.707
13.84	0.247	0.42	0.726
15.11	0.230	0.39	0.742
16.38	0.214	0.365	0.751
17.65	0.199	0.345	0.751
18.92	0.186	0.32	0.775
20.19	0.174	0.30	0.791
21.46	0.164	0.28	0.820
22.73	0.154	0.265	0.832
24.0	0.146	0.25	0.859
25.27	0.139	0.225	0.959.
26.54	———	0.20	———
27.81	———	0.11	———
29.08	———	———	———

wide - 0.769 ± 0.052

narrow - 0.794 ± 0.033

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3 DATE: DEC. 11/87

Additions made to sample: Atm.: H.P. Ar (gettered)

100g as-received + 0.13g SiO_2 + 5.0g Fe_2O_3

Total wt. of sample: 105.13g Total wt. w/crucible: init.- 156.10g

finl.- 155.95g

RUN#: 3 TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	99	0.0	1.94
1	60	4.95	0.79
1	40	7.49	0.63
1	20	10.03	0.52
1	10	11.3	0.48
1	0	12.57	0.445
1	990	13.84	0.415
1	980	15.11	0.39
1	970	16.38	0.36
1	960	17.65	0.34
1	950	18.92	0.315
1	940	20.19	0.29
1	930	21.46	0.27
1	920	22.73	0.25
1	910	24.0	0.23
1	900	25.27	0.21
1	890	26.54	0.185
1	880	27.81	0.10
1	876	BOTTOM: ~~29.08~~	0.08
		Depth. 28.3 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.94	—
4.95	—	0.79	—
7.49	—	0.63	—
10.03	0.305	0.52	0.693
11.3	0.284	0.48	0.710
12.57	0.265	0.445	0.726
13.84	0.247	0.415	0.737
15.11	0.230	0.39	0.742
16.38	0.214	0.36	0.764
17.65	0.199	0.34	0.765
18.92	0.186	0.315	0.791
20.19	0.174	0.29	0.829
21.46	0.164	0.27	0.863
22.73	0.154	0.25	0.906
24.0	0.146	0.23	0.973
25.27	0.139	0.21	1.069
26.54	—	0.185	—
27.81	—	0.10	—
29.08	—	—	—

wide - 0.801 ± 0.083

narrow - 0.831 ± 0.056

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 11/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar.

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#1+3)
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.85	2.0	1.94	1.895
4.95	0.78	0.795	0.79	0.785
7.49	0.61	0.63	0.63	0.620
10.03	0.51	0.53	0.52	0.515
11.3	0.465	0.485	0.48	0.473
12.57	0.44	0.455	0.445	0.443
13.84	0.40	0.42	0.415	0.408
15.11	0.39	0.39	0.39	0.390
16.38	0.36	0.365	0.36	0.360
17.65	0.34	0.345	0.34	0.340
18.92	0.315	0.32	0.315	0.315
20.19	0.295	0.30	0.29	0.293
21.46	0.27	0.28	0.27	0.270
22.73	0.25	0.265	0.25	0.250
24.0	0.23	0.25	0.23	0.230
25.27	0.21	0.225	0.21	0.210
26.54	0.18	0.20	0.185	0.183
27.81	0.10	0.11	0.10	0.100
~~29.08~~				
	Rest. 0.08 —	Rest 0.08 —	Rest. 0.08 —	0.08 Rest.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (1+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	1.895	———
4.95	———	0.785	———
7.49	———	0.620	———
10.03	0.305	0.515	0.701
11.3	0.284	0.473	0.723
12.57	0.265	0.443	0.730
13.84	0.247	0.408	0.753
15.11	0.230	0.390	0.742
16.38	0.214	0.360	0.764
17.65	0.199	0.340	0.765
18.92	0.186	0.315	0.791
20.19	0.174	0.293	0.817
21.46	0.164	0.270	0.863
22.73	0.154	0.250	0.906
24.0	0.146	0.230	0.973
25.27	0.139	0.210	1.069
26.54	———	0.183	———
27.81	———	0.100	———
29.08	———	———	———

wide - 0.802 ± 0.080.

narrow - 0.828 ± 0.056.

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 11/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 0.95 Fe/SiO$_2$ with 5 wt.% Fe$_2$O$_3$

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.85	2.0	1.94	1.93
4.95	0.78	0.795	0.79	0.788
7.49	0.61	0.63	0.63	0.623
10.03	0.51	0.53	0.52	0.520
11.3	0.465	0.485	0.48	0.477
12.57	0.44	0.455	0.445	0.447
13.84	0.40	0.42	0.415	0.412
15.11	0.39	0.39	0.39	0.390
16.38	0.36	0.365	0.36	0.362
17.65	0.34	0.345	0.34	0.342
18.92	0.315	0.32	0.315	0.317
20.19	0.295	0.30	0.29	0.295
21.46	0.27	0.28	0.27	0.273
22.73	0.25	0.265	0.25	0.255
24.0	0.23	0.25	0.23	0.237
25.27	0.21	0.225	0.21	0.215
26.54	0.18	0.20	0.185	0.188
27.81	0.10	0.11	0.10	0.103
~~29.08~~				
	Rext. 0.08	Rext. 0.08	Rext. 0.08	Rext. 0.08

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5 wt.% Fe_2O_3

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	1.93	———
4.95	———	0.788	———
7.49	———	0.623	———
10.03	0.305	0.520	0.693
11.3	0.284	0.477	0.715
12.57	0.265	0.447	0.722
13.84	0.247	0.412	0.744
15.11	0.230	0.390	0.742
16.38	0.214	0.362	0.759
17.65	0.199	0.342	0.760
18.92	0.186	0.317	0.784
20.19	0.174	0.295	0.809
21.46	0.164	0.273	0.850
22.73	0.154	0.255	0.880
24.0	0.146	0.237	0.930
25.27	0.139	0.215	1.030
26.54	———	0.188	———
27.81	———	0.103	———
29.08	———	———	———

wide - 0.790 ± 0.069

narrow - 0.817 ± 0.049.

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2

DATE: DEC. 17/87

Additions made to sample:

100g as-received + 2.69g Fe_2O_3 + 0.94g Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.63g

Total wt. w/crucible: init.- 152.82g

finl.- 152.72g

RUN#: 1

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	98	0.0	2.8
3	59	4.95	1.05
1	39	7.49	0.84
1	19	10.03	0.685
1	09	11.3	0.625
1	999	12.57	0.575
1	989	13.84	0.535
1	979	15.11	0.50
1	969	16.38	0.465
1	959	17.65	0.435
1	949	18.92	0.405
1	939	20.19	0.38
1	929	21.46	0.35
1	919	22.73	0.325
1	909	24.0	0.30
1 (0.3)	899	25.27	0.27 (0.285)
1 (0.3)	889	26.54	0.215 (0.235)
1 (0.3)	880	BOTTOM ~~27.81~~	0.06 (0.09)
		29.08	
		Depth 27.7 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: HP. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	2.8	———
4.95	———	1.05	———
7.49	———	0.84	———
10.03	0.305	0.685	0.488
11.3	0.284	0.625	0.503
12.57	0.265	0.575	0.515
13.84	0.247	0.535	0.520
15.11	0.230	0.50	0.523
16.38	0.214	0.465	0.528
17.65	0.199	0.435	0.531
18.92	0.186	0.405	0.539
20.19	0.174	0.38	0.544
21.46	0.164	0.35	0.566
22.73	0.154	0.325	0.581
24.0	0.146	0.30	0.608
25.27	0.139	0.27	0.662
26.54	———	0.215	———
27.81	———	———	———
29.08	———	———	———

wide - 0.542 ± 0.031

narrow - 0.552 ± 0.021

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2

DATE: DEC. 17/87

Additions made to sample:

100 g as-received + 2.69 g Fe_2O_3 + 0.94 g Fe powder

Atm.: H.P. Ar (gettered).

Total wt. of sample: 103.63 g

Total wt. w/crucible: init.- 152.82 g
finl.- 152.72 g

RUN#: 2

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	99	0.0	2.7
3	60	4.95	1.0
1	40	7.49	0.835
1	20	10.03	0.695
1	10	11.3	0.64
1	0	12.57	0.58
1	990	13.84	0.54
1	980	15.11	0.505
1	970	16.38	0.47
1	960	17.65	0.44
1	950	18.92	0.41
1	940	20.19	0.385
1	930	21.46	0.36
1	920	22.73	0.33
1	910	24.0	0.30
1 (0.3)	900	25.27	0.28 (0.3)
1(0.3)	890	26.54	0.225 (0.24)
1(0.3)	882	BOTTOM. ~~27.81~~	0.06 (0.09)
		29.08	
		Depth. 27.6 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: HP. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.7	—
4.95	—	1.0	—
7.49	—	0.835	—
10.03	0.305	0.695	0.480
11.3	0.284	0.64	0.490
12.57	0.265	0.58	0.510
13.84	0.247	0.54	0.515
15.11	0.230	0.505	0.517
16.38	0.214	0.47	0.522
17.65	0.199	0.44	0.524
18.92	0.186	0.41	0.531
20.19	0.174	0.385	0.535
21.46	0.164	0.36	0.547
22.73	0.154	0.33	0.570
24.0	0.146	0.30	0.608
25.27	0.139	0.28	0.632
26.54	—	0.225	—
27.81	—	—	—
29.08	—	—	—

wide — 0.534 ± 0.032

narrow — 0.541 ± 0.018

SLAG CONDUCTIVITY DETERMINATION

X

SLAG SAMPLE: 1.05 Fe/SiO_2

DATE: DEC. 17/87

Additions made to sample:

100 g as-received + 2.69 g Fe_2O_3 + 0.94 g Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.63 g

Total wt. w/crucible: init.- 152.82 g
finl.- 152.72 g

RUN#: 3

TEMPERATURE: 1250°C ± 5'

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	99	0.0	2.8
3	60	4.95	1.05
1	40	7.49	0.85
1	20	10.03	0.71
1	10	11.3	0.65
1	0	12.57	0.60
1	990	13.84	0.56
1	980	15.11	0.525
1	970	16.38	0.49
1	960	17.65	0.46
1	950	18.92	0.43
1	940	20.19	0.40
1	930	21.46	0.375
1	920	22.73	0.35
1	910	24.0	0.32
1 (0.3)	900	25.27	0.285 (0.295)
1 (0.3)	890	26.54	0.23 (0.245)
1 (0.3)	882	BOTTOM. 27.81	0.06 (0.09)
		~~29.08~~	
		Depth. 27.6 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: HP. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.8	—
4.95	—	1.05	—
7.49	—	0.85	—
10.03	0.305	0.71	0.469
11.3	0.284	0.65	0.481
12.57	0.265	0.60	0.491
13.84	0.247	0.56	0.494
15.11	0.230	0.525	0.495
16.38	0.214	0.49	0.498
17.65	0.199	0.46	0.498
18.92	0.186	0.43	0.503
20.19	0.174	0.40	0.512
21.46	0.164	0.375	0.520
22.73	0.154	0.35	0.531
24.0	0.146	0.32	0.561
25.27	0.139	0.285	0.618
26.54	—	0.23	—
27.81	—	—	—
29.08	—	—	—

wide – 0.508 ± 0.023

narrow – 0.513 ± 0.013

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 1.05 Fe/SiO_2

TEMPERATURE: 1250°C ± 5°

DATE: DEC. 17/87

Atm.: HP. Ar

DEPTH (mm)	RESISTANCE (ohms)			AVG. (1+2)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.8	2.7	2.8	2.750
4.95	1.05	1.0	1.05	1.025
7.49	0.84	0.835	0.85	0.838
10.03	0.685	0.695	0.71	0.690
11.3	0.625	0.64	0.65	0.633
12.57	0.575	0.58	0.60	0.578
13.84	0.535	0.54	0.56	0.538
15.11	0.50	0.505	0.525	0.503
16.38	0.465	0.47	0.49	0.468
17.65	0.435	0.44	0.46	0.438
18.92	0.405	0.41	0.43	0.408
20.19	0.38	0.385	0.40	0.383
21.46	0.35	0.36	0.375	0.355
22.73	0.325	0.33	0.35	0.328
24.0	0.30	0.30	0.32	0.300
25.27	0.27	0.28	0.285	0.275
26.54	0.215	0.225	0.23	0.220
~~27.81~~				
~~29.08~~	Rext 0.06 —	Rext 0.06 —	Rext 0.06 —	0.06 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO$_2$

Atm.: HP. Ar

TEMPERATURE: ~~1300°C ± 5~~ 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (1+2) (ohm)	CONDUCTIVITY (ohm^{-1}.cm^{-1})
0.0	—	2.750	—
4.95	—	1.025	—
7.49	—	0.838	—
10.03	0.305	0.690	0.484
11.3	0.284	0.633	0.496
12.57	0.265	0.578	0.512
13.84	0.247	0.538	0.517
15.11	0.230	0.503	0.519
16.38	0.214	0.468	0.525
17.65	0.199	0.438	0.526
18.92	0.186	0.408	0.534
20.19	0.174	0.383	0.539
21.46	0.164	0.355	0.556
22.73	0.154	0.328	0.575
24.0	0.146	0.300	0.608
25.27	0.139	0.275	0.647
26.54	—	0.220	—
27.81	—	—	—
29.08	—	—	—

wide - 0.537 ± 0.032

narrow - 0.546 ± 0.020

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 17/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 1.05 Fe/SiO_2

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.8	2.7	2.8	2.77
4.95	1.05	1.0	1.05	1.03
7.49	0.84	0.835	0.85	0.842
10.03	0.685	0.695	0.71	0.697
11.3	0.625	0.64	0.65	0.638
12.57	0.575	0.58	0.60	0.585
13.84	0.535	0.54	0.56	0.545
15.11	0.50	0.505	0.525	0.510
16.38	0.465	0.47	0.49	0.475
17.65	0.435	0.44	0.46	0.445
18.92	0.405	0.41	0.43	0.415
20.19	0.38	0.385	0.40	0.388
21.46	0.35	0.36	0.375	0.362
22.73	0.325	0.33	0.35	0.335
24.0	0.30	0.30	0.32	0.307
25.27	0.27	0.28	0.285	0.278
26.54	0.215	0.225	0.23	0.223
~~27.81~~				
~~29.08~~	Rext. 0.06	Rext. 0.06	Rext. 0.06	Rext 0.06.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.77	—
4.95	—	1.03	—
7.49	—	0.842	—
10.03	0.305	0.697	0.479
11.3	0.284	0.638	0.491
12.57	0.265	0.585	0.505
13.84	0.247	0.545	0.509
15.11	0.230	0.510	0.511
16.38	0.214	0.475	0.516
17.65	0.199	0.445	0.517
18.92	0.186	0.415	0.524
20.19	0.174	0.388	0.530
21.46	0.164	0.362	0.543
22.73	0.154	0.335	0.560
24.0	0.146	0.307	0.591
25.27	0.139	0.278	0.638
26.54	—	0.223	—
27.81	—	—	—
29.08	—	—	—

wide - 0.527 ± 0.028

narrow - 0.535 ± 0.017

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2

DATE: DEC. 17/87

Additions made to sample:

100 g as-received + 2.69 g Fe_2O_3 + 0.94 g Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.63g

Total wt. w/crucible: **init**.- 152.82g
finl.- 152.72g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	98	0.0	2.2
1	59	4.95	0.92
1	39	7.49	0.72
1	19	10.03	0.695
1	09	11.3	0.55
1	999	12.57	0.51
1	989	13.84	0.48
1	979	15.11	0.445
1	969	16.38	0.42
1	959	17.65	0.395
1	949	18.92	0.37
1	939	20.19	0.35
1	929	21.46	0.33
1	919	22.73	0.305
1	909	24.0	0.30
1 (0.3)	899	25.27	0.26 (0.270)
1 (0.3)	889	26.54	0.16 (0.175)
1 (0.3)	883	BOTTOM. ~~27.81~~	0.12 (0.14)
		29.08	
		Depth. 27.3mm	

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.12 Ω RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.2	—
4.95	—	0.92	—
7.49	—	0.72	—
10.03	0.305	0.695	0.575
11.3	0.284	0.55	0.660
12.57	0.265	0.51	0.679
13.84	0.247	0.48	0.686
15.11	0.230	0.445	0.708
16.38	0.214	0.42	0.713
17.65	0.199	0.395	0.724
18.92	0.186	0.37	0.744
20.19	0.174	0.35	0.757
21.46	0.164	0.33	0.781
22.73	0.154	0.305	0.832
24.0	0.146	0.30	0.811
25.27	0.139	0.26	0.993
26.54	—	0.16	—
27.81	—	—	—
29.08	—	—	—

wide – 0.736 ± 0.055

narrow – 0.715 ± 0.021

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2

DATE: DEC. 17/87

Additions made to sample:

100g as-received + 2.69g Fe_2O_3 + 0.94 Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.63g

Total wt. w/crucible: init.- 152.82g

finl.- 152.72g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	100	0.0	2.4
1	61	4.95	0.94
1	41	7.49	0.74
1	21	10.03	0.62
1	11	11.3	0.57
1	01	12.57	0.52
1	991	13.84	0.49
1	981	15.11	0.45
1	971	16.38	0.42
1	961	17.65	0.395
1	951	18.92	0.37
1	941	20.19	0.35
1	931	21.46	0.325
1	921	22.73	0.30
1 (0.3)	911	24.0	0.28 (0.285)
1 (0.3)	901	25.27	0.25 (0.255)
1 (0.3)	891	26.54	0.20 (0.215)
1 (0.3)	882 BOTTOM.	~~27.81~~	0.12 (0.145)
		29.08	
		Depth. 27.7 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 1.05 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 17/87

Atm.: HP. Ar

$r_{ext.}$ = 0.12 Ω RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.4	—
4.95	—	0.94	—
7.49	—	0.74	—
10.03	0.305	0.62	0.610
11.3	0.284	0.57	0.631
12.57	0.265	0.52	0.663
13.84	0.247	0.49	0.668
15.11	0.230	0.45	0.697
16.38	0.214	0.42	0.713
17.65	0.199	0.395	0.724
18.92	0.186	0.37	0.744
20.19	0.174	0.35	0.757
21.46	0.164	0.325	0.800
22.73	0.154	0.30	0.856
24.0	0.146	0.28	0.913
25.27	0.139	0.25	1.069
26.54	—	0.20	—
27.81	—	—	—
29.08	—	—	—

wide - 0.742 ± 0.085

narrow - 0.709 ± 0.029.

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2

DATE: DEC. 17/87

Additions made to sample:

100g as-received + 2.69g Fe_2O_3 + 0.94g Fe powder.

Atm.: H.P. Ar (gettered)

Total wt. of sample: 103.63g

Total wt. w/crucible: **init.**- 152.82g
finl.- 152.72g

RUN#: 3

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	100	0.0	2.4
1	61	4.95	0.95
1	41	7.49	0.74
1	21	10.03	0.61
1	11	11.3	0.56
1	01	12.57	0.52
1	991	13.84	0.48
1	981	15.11	0.44
1	971	16.38	0.42
1	961	17.65	0.39
1	951	18.92	0.365
1	941	20.19	0.34
1	931	21.46	0.32
1	921	22.73	0.29
1 (0.3)	911	24.0	0.27 (0.285)
1 (0.3)	901	25.27	0.24 (0.26)
1 (0.3)	891	26.54	0.20 (0.22)
1 (0.3)	882 BOTTOM.	~~27.81~~	0.12 (0.14)
		29.08	
		Depth. 27.7 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: H.P. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.} = 0.12\ \Omega$

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	——	2.4	——
4.95	——	0.95	——
7.49	——	0.74	——
10.03	0.305	0.61	0.622
11.3	0.284	0.56	0.645
12.57	0.265	0.52	0.663
13.84	0.247	0.48	0.686
15.11	0.230	0.44	0.719
16.38	0.214	0.42	0.713
17.65	0.199	0.39	0.737
18.92	0.186	0.365	0.759
20.19	0.174	0.34	0.791
21.46	0.164	0.32	0.820
22.73	0.154	0.29	0.906
24.0	0.146	0.27	0.973
25.27	0.139	0.24	1.158
26.54	——	0.20	——
27.81	——	——	——
29.08	——	——	——

wide – 0.765 ± 0.102

narrow – 0.723 ± 0.027

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 17/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar.

SLAG SAMPLE: 1.05 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#2+3).
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.2	2.4	2.4	2.40.
4.95	0.92	0.94	0.95	0.945
7.49	0.72	0.74	0.74	0.740
10.03	0.695	0.62	0.61	0.615
11.3	0.55	0.57	0.56	0.565
12.57	0.51	0.52	0.52	0.520
13.84	0.48	0.49	0.48	0.485
15.11	0.445	0.45	0.44	0.445
16.38	0.42	0.42	0.42	0.420
17.65	0.395	0.395	0.39	0.393
18.92	0.37	0.37	0.365	0.368
20.19	0.35	0.35	0.34	0.345
21.46	0.33	0.325	0.32	0.323
22.73	0.305	0.30	0.29	0.295
24.0	0.30	0.28	0.27	0.275
25.27	0.26	0.25	0.24	0.245
26.54	0.16	0.20	0.20	0.200
27.81				
~~29.08~~	Rext. 0.12 —	Rext 0.12 —	Rext. 0.12 —	Rext. 0.12

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: HP Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.12 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.40	—
4.95	—	0.945	—
7.49	—	0.740	—
10.03	0.305	0.615	0.616
11.3	0.284	0.565	0.638
12.57	0.265	0.520	0.663
13.84	0.247	0.485	0.677
15.11	0.230	0.445	0.708
16.38	0.214	0.420	0.713
17.65	0.199	0.393	0.729
18.92	0.186	0.368	0.750
20.19	0.174	0.345	0.773
21.46	0.164	0.323	0.808
22.73	0.154	0.295	0.880
24.0	0.146	0.275	0.942
25.27	0.139	0.245	1.112
26.54	—	0.200	—
27.81	—	—	—
29.08	—	—	—

wide - 0.753 ± 0.093

narrow - 0.715 ± 0.027

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 17/87

X

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar

SLAG SAMPLE: 1.05 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (#1+2)
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.2	2.4	2.4	2.30
4.95	0.92	0.94	0.95	[illegible] 0.930
7.49	0.72	0.74	0.74	0.730
10.03	~~0.695~~	0.62	0.61	0.620
11.3	0.55	0.57	0.56	0.560
12.57	0.51	0.52	0.52	0.515
13.84	0.48	0.49	0.48	0.485
15.11	0.445	0.45	0.44	0.448
16.38	0.42	0.42	0.42	0.420
17.65	0.395	0.395	0.39	0.395
18.92	0.37	0.37	0.365	0.370
20.19	0.35	0.35	0.34	0.350
21.46	0.33	0.325	0.32	0.328
22.73	0.305	0.30	0.29	0.303
24.0	0.30	0.28	0.27	0.290
25.27	0.26	0.25	0.24	0.255
26.54	~~0.16~~	0.20	0.20	0.200
~~27.81~~				
~~29.08~~	Rext. 0.12 —	Rext. 0.12 —	Rext 0.12 —	0.12 Rext.

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: HP. Ar.

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.12 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (1+2)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.30	—
4.95	—	0.930	—
7.49	—	0.730	—
10.03	0.305	0.620	0.610
11.3	0.284	0.560	0.645
12.57	0.265	0.515	0.671
13.84	0.247	0.485	0.677
15.11	0.230	0.448	0.701
16.38	0.214	0.420	0.713
17.65	0.199	0.395	0.724
18.92	0.186	0.370	0.744
20.19	0.174	0.350	0.757
21.46	0.164	0.328	0.788
22.73	0.154	0.303	0.842
24.0	0.146	0.290	0.859
25.27	0.139	0.255	1.030
26.54	—	0.200	—
27.81	—	—	—
29.08	—	—	—

wide - 0.738 ± 0.069

narrow - 0.712 ± 0.025

SLAG CONDUCTIVITY DETERMINATION

SUMMARY OF RESISTANCE MEASUREMENTS:

SLAG SAMPLE: 1.05 Fe/SiO_2

TEMPERATURE: 1300°C ± 5°

DATE: DEC. 17/87

Atm.: H.P. Ar (gettered)

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	2.2	2.4	2.4	2.33
4.95	0.92	0.94	0.95	0.937
7.49	0.72	0.74	0.74	0.733
10.03	~~0.695~~	0.62	0.61	0.615
11.3	0.55	0.57	0.56	0.560
12.57	0.51	0.52	0.52	0.517
13.84	0.48	0.49	0.48	0.483
15.11	0.445	0.45	0.44	0.445
16.38	0.42	0.42	0.42	0.420
17.65	0.395	0.395	0.39	0.393
18.92	0.37	0.37	0.365	0.368
20.19	0.35	0.35	0.34	0.347
21.46	0.33	0.325	0.32	0.325
22.73	0.305	0.30	0.29	0.298
24.0	0.30	0.28	0.27	0.283
25.27	0.26	0.25	0.24	0.250
26.54	~~0.16~~	0.20	0.20	0.200
~~27.81~~				
~~29.08~~	Rext. 0.12	Rext. 0.12	Rext. 0.12	Rext. 0.12

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2

Atm.: H.P. Ar (gettered).

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.12 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1} \cdot cm^{-1}$)
0.0	—	2.33	—
4.95	—	0.937	—
7.49	—	0.733	—
10.03	0.305	0.615	0.616
11.3	0.284	0.560	0.645
12.57	0.265	0.517	0.668
13.84	0.247	0.483	0.680
15.11	0.230	0.445	0.708
16.38	0.214	0.420	0.713
17.65	0.199	0.393	0.729
18.92	0.186	0.368	0.750
20.19	0.174	0.347	0.767
21.46	0.164	0.325	0.800
22.73	0.154	0.298	0.865
24.0	0.146	0.283	0.896
25.27	0.139	0.250	1.070
26.54	—	0.200	—
27.81	—	—	—
29.08	—	—	—

wide – 0.747 ± 0.08

narrow – 0.716 ± 0.02

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3

DATE: DEC. 19/87

Additions made to sample:

100g as-received + 7.87g Fe_2O_3 + 0.94g Fe powder.

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.81g

Total wt. w/crucible: init.- 157.85g
finl.- 157.67g

RUN#: 1

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	121	0.0	1.75
1	82	4.95	0.76
1	62	7.49	0.61
1	42	10.03	0.52
1	32	11.3	0.48
1	22	12.57	0.44
1	12	13.84	0.41
1	02	15.11	0.38
1	992	16.38	0.355
1	982	17.65	0.33
1	972	18.92	0.31
1	962	20.19	0.29
1 (0.3)	952	21.46	0.265 (0.28)
1 (0.3)	942	22.73	0.25 (0.265)
1 (0.3)	932	24.0	0.23 (0.245)
1 (0.3)	922	25.27	0.205 (0.224)
1 (0.3)	912	26.54	0.18 (0.197)
1 (0.3)	902	27.81	0.08 (0.10)
1 (0.3)	899	BOTTOM ~~29.08~~	0.075 (0.091)
		Depth. 28.2 mm.	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5% Fe_2O_3

TEMPERATURE: 1250 °C ± 5°

DATE: DEC. 19/87

Atm.: HP. Ar

$r_{ext.}$ = 0.075

RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.75	—
4.95	—	0.76	—
7.49	—	0.61	—
10.03	0.305	0.52	0.685
11.3	0.284	0.48	0.701
12.57	0.265	0.44	0.726
13.84	0.247	0.41	0.737
15.11	0.230	0.38	0.754
16.38	0.214	0.355	0.764
17.65	0.199	0.33	0.780
18.92	0.186	0.31	0.791
20.19	0.174	0.29	0.809
21.46	0.164	0.265	0.863
22.73	0.154	0.25	0.880
24.0	0.146	0.23	0.942
25.27	0.139	0.205	1.069.
26.54	—	0.18	—
27.81	—	0.08	—
29.08	—	—	—

wide – 0.795 ± 0.073

narrow – 0.765 ± 0.022

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3 DATE: DEC. 19/87

Additions made to sample:

100 g as-received + 7.87 g Fe_2O_3 + 0.94 g Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.81 g

Total wt. w/crucible: init. - 157.85 g

finl. - 157.67 g

RUN#: 2 TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	125	0.0	2.5
1	86	4.95	0.82
1	66	7.49	0.64
1	46	10.03	0.525
1	36	11.3	0.48
1	26	12.57	0.44
1	16	13.84	0.40
1	06	15.11	0.38
1	996	16.38	0.35
1	986	17.65	0.325
1	976	18.92	0.30
1	966	20.19	0.28
1 (0.3)	956	21.46	0.26 (0.290)
1 (0.3)	946	22.73	0.25 (0.272)
1 (0.3)	936	24.0	0.23 (0.252)
1 (0.3)	926	25.27	0.21 (0.233)
1 (0.3)	916	26.54	0.18 (0.21)
1 (0.3)	906	27.81	0.145 (0.17)
1 (0.3)	899	BOTTOM ~~29.08~~	0.06 (0.09)
		Depth. 28.9 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3

Atm.: HP. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.5	—
4.95	—	0.82	—
7.49	—	0.64	—
10.03	0.305	0.525	0.656
11.3	0.284	0.48	0.676
12.57	0.265	0.44	0.697
13.84	0.247	0.40	0.726
15.11	0.230	0.38	0.719
16.38	0.214	0.35	0.738
17.65	0.199	0.325	0.751
18.92	0.186	0.30	0.775
20.19	0.174	0.28	0.791
21.46	0.164	0.26	0.820
22.73	0.154	0.25	0.811
24.0	0.146	0.23	0.859
25.27	0.139	0.21	0.927
26.54	—	0.18	—
27.81	—	0.145	—
29.08	—	—	—

wide – 0.760 ± 0.056

narrow – 0.742 ± 0.022

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 19/87

Additions made to sample:

100g as-received + 7.87g Fe_2O_3 + 0.94g Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.81g

Total wt. w/crucible: init.- 157.85g

finl.- 157.67g

RUN#: 3

TEMPERATURE: 1250°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	123	0.0	1.87
1	84	4.95	0.82
1	64	7.49	0.64
1	44	10.03	0.525
1	34	11.3	0.48
1	24	12.57	0.44
1	14	13.84	0.41
1	04	15.11	0.38
1	994	16.38	0.35
1	984	17.65	0.33
1	974	18.92	0.305
1	964	20.19	0.28
1 (0.3)	954	21.46	0.26 (0.29)
1 (0.3)	944	22.73	0.245 (0.27)
1 (0.3)	934	24.0	0.22 (0.25)
1 (0.3)	924	25.27	0.20 (0.23)
1 (0.3)	914	26.54	0.175 (0.205)
1 (0.3)	904	27.81	0.11 (0.14)
1 (0.3)	899	BOTTOM ~~29.08~~	0.06 (0.095)
		Depth. 28.4 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3

Atm.: HP. Ar

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06 Ω

RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.87	—
4.95	—	0.82	—
7.49	—	0.64	—
10.03	0.305	0.525	0.656
11.3	0.284	0.48	0.676
12.57	0.265	0.44	0.697
13.84	0.247	0.41	0.706
15.11	0.230	0.38	0.719
16.38	0.214	0.35	0.738
17.65	0.199	0.33	0.737
18.92	0.186	0.305	0.759
20.19	0.174	0.28	0.791
21.46	0.164	0.26	0.820
22.73	0.154	0.245	0.832
24.0	0.146	0.22	0.913
25.27	0.139	0.20	0.993
26.54	—	0.175	—
27.81	—	0.11	—
29.08	—	—	—

wide – 0.763 ± 0.071

narrow – 0.732 ± 0.020

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 19/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: HP. Ar

SLAG SAMPLE: 1.05 Fe/SiO$_2$ with 5wt.% Fe$_2$O$_3$

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG. (2+3).
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.75	2.5	1.87	2.185
4.95	0.76	0.82	0.82	0.820
7.49	0.61	0.64	0.64	0.640
10.03	0.52	0.525	0.525	0.525
11.3	0.48	0.48	0.48	0.480
12.57	0.44	0.44	0.44	0.440
13.84	0.41	0.40	0.41	0.405
15.11	0.38	0.38	0.38	0.380
16.38	0.355	0.35	0.35	0.350
17.65	0.33	0.325	0.33	0.328
18.92	0.31	0.30	0.305	0.303
20.19	0.29	0.28	0.28	0.280
21.46	0.265	0.26	0.26	0.260
22.73	0.25	0.25	0.245	0.248
24.0	0.23	0.23	0.22	0.225
25.27	0.205	0.21	0.20	0.205
26.54	0.18	0.18	0.175	0.178
27.81	0.08	0.145	0.11	0.128.
29.08	Rext. 0.075	Rext 0.06	Rext. 0.06 —	Rext 0.06

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5wt% Fe_2O_3

Atm.: HP. Ar.

TEMPERATURE: 1250°C ± 5°

$r_{ext.}$ = 0.06Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#2+3)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.185	—
4.95	—	0.820	—
7.49	—	0.640	—
10.03	0.305	0.525	0.656
11.3	0.284	0.480	0.676
12.57	0.265	0.440	0.697
13.84	0.247	0.405	0.716
15.11	0.230	0.380	0.719
16.38	0.214	0.350	0.738
17.65	0.199	0.328	0.743
18.92	0.186	0.303	0.765
20.19	0.174	0.280	0.791
21.46	0.164	0.260	0.820
22.73	0.154	0.248	0.819
24.0	0.146	0.225	0.885
25.27	0.139	0.205	0.959
26.54	—	0.178	—
27.81	—	0.128	—
29.08	—	—	—

wide - 0.761 ± 0.063

narrow - 0.736 ± 0.020

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 19/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3

TEMPERATURE: 1250°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.75	2.5	1.87	2.04
4.95	0.76	0.82	0.82	0.80
7.49	0.61	0.64	0.64	0.63
10.03	0.52	0.525	0.525	0.523
11.3	0.48	0.48	0.48	0.480
12.57	0.44	0.44	0.44	0.440
13.84	0.41	0.40	0.41	0.407
15.11	0.38	0.38	0.38	0.380
16.38	0.355	0.35	0.35	0.352
17.65	0.33	0.325	0.33	0.328
18.92	0.31	0.30	0.305	0.305
20.19	0.29	0.28	0.28	0.283
21.46	0.265	0.26	0.26	0.262
22.73	0.25	0.25	0.245	0.248
24.0	0.23	0.23	0.22	0.227
25.27	0.205	0.21	0.20	0.205
26.54	0.18	0.18	0.175	0.178
27.81	0.08	0.145	0.11	—
29.08	Rext. 0.075	Rext. 0.06	Rext. 0.06	Rext. 0.06

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION: DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3 Atm.: H.P. Ar (gettered)

TEMPERATURE: 1250°C ± 5° $r_{ext.}$ = 0.06 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	2.04	—
4.95	—	0.80	—
7.49	—	0.63	—
10.03	0.305	0.523	0.659
11.3	0.284	0.480	0.676
12.57	0.265	0.440	0.697
13.84	0.247	0.407	0.712
15.11	0.230	0.380	0.719
16.38	0.214	0.352	0.733
17.65	0.199	0.328	0.743
18.92	0.186	0.305	0.759
20.19	0.174	0.283	0.780
21.46	0.164	0.262	0.812
22.73	0.154	0.248	0.819
24.0	0.146	0.227	0.874
25.27	0.139	0.205	0.959
26.54	—	0.178	—
27.81	—	—	—
29.08	—	—	—

wide – 0.757 ± 0.060

narrow – 0.733 ± 0.019

X

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3

DATE: DEC. 19/87

Additions made to sample:

100g as-received + 7.87g Fe_2O_3 + 0.94 Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.81g

Total wt. w/crucible: init.- 157.85g

finl.- 157.67g

RUN#: 1

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	127	0.0	1.8
1	88	4.95	0.73
1	68	7.49	0.57
1	48	10.03	0.465
1	38	11.3	0.43
1	28	12.57	0.405
1	18	13.84	0.38
1	08	15.11	0.35
1	998	16.38	0.33
1	988	17.65	0.30
1	978	18.92	0.28
1 (0.3)	968	20.19	0.265 (0.295)
1 (0.3)	958	21.46	0.25 (0.275)
1 (0.3)	948	22.73	0.23 (0.257)
1 (0.3)	938	24.0	0.21 (0.24)
1 (0.3)	928	25.27	0.195 (0.225)
1 (0.3)	918	26.54	0.175 (0.205)
1 (0.3)	908	27.81	0.140 (0.175)
1 (0.3)	899	BOTTOM ~~29.08~~	0.07 (0.10)
		Depth. 28.9 mm.	

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5% Fe_2O_3

Atm.: H.P. Ar

TEMPERATURE: 1300 °C ± 5°

$r_{ext.}$ = 0.07 Ω RUN#: 1

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.8	—
4.95	—	0.73	—
7.49	—	0.57	—
10.03	0.305	0.465	0.772
11.3	0.284	0.43	0.789
12.57	0.265	0.405	0.791
13.84	0.247	0.38	0.797
15.11	0.230	0.35	0.821
16.38	0.214	0.33	0.823
17.65	0.199	0.30	0.865
18.92	0.186	0.28	0.886
20.19	0.174	0.265	0.892
21.46	0.164	0.25	0.911
22.73	0.154	0.23	0.963
24.0	0.146	0.21	1.043
25.27	0.139	0.195	1.112
26.54	—	0.175	—
27.81	—	0.140	—
29.08	—	—	—

wide: 0.871 ± 0.080

narrow: 0.939 ± 0.066

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5wt.% Fe_2O_3

DATE: DEC. 18/87

Additions made to sample:

100g as-received + 7.87g Fe_2O_3 + 0.94g Fe powder

Atm.: H.P. Ar (gettered)

Total wt. of sample: 108.81g

Total wt. w/crucible: init.- 157.85g
finl.- 157.67g

RUN#: 2

TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	127	0.0	1.92
1	88	4.95	0.77
1	68	7.49	0.60
1	48	10.03	0.50
1	38	11.3	0.46
1	28	12.57	0.425
1	18	13.84	0.395
1	08	15.11	0.365
1	998	16.38	0.34
1	988	17.65	0.315
1	978	18.92	0.295
1 (0.3)	968	20.19	0.275 (0.295)
1 (0.3)	958	21.46	0.26 (0.28)
1 (0.3)	948	22.73	0.24 (0.265)
1 (0.3)	938	24.0	0.22 (0.245)
1 (0.3)	928	25.27	0.20 (0.227)
1 (0.3)	918	26.54	0.18 (0.21)
1 (0.3)	908	27.81	0.16 (0.182)
1 (0.3)	899	BOTTOM ~~29.08~~	0.08 (0.11)
		Depth. 28.9 mm	

CONDUCTIVITY CALCULATION:

SLAG SAMPLE: 1.05 Fe / SiO_2 with 5 wt.% Fe_2O_3

TEMPERATURE: 1300 °C ± 5°

DATE: DEC. 19/87

Atm.: H.P. Ar

$r_{ext.}$ = 0.08 Ω

RUN#: 2

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.92	—
4.95	—	0.77	—
7.49	—	0.60	—
10.03	0.305	0.50	0.726
11.3	0.284	0.46	0.747
12.57	0.265	0.425	0.768
13.84	0.247	0.395	0.784
15.11	0.230	0.365	0.807
16.38	0.214	0.34	0.823
17.65	0.199	0.315	0.847
18.92	0.186	0.295	0.865
20.19	0.174	0.275	0.892
21.46	0.164	0.26	0.911
22.73	0.154	0.24	0.963
24.0	0.146	0.22	1.043
25.27	0.139	0.20	1.158
26.54	—	0.18	—
27.81	—	0.16	—
29.08	—	—	—

wide - ~~0.939~~ / 0.859 ± 0.089

narrow - 0.935 ± 0.070

SLAG CONDUCTIVITY DETERMINATION

SLAG SAMPLE: 1.05 Fe/SiO₂ with 5wt.% Fe₂O₃. DATE: DEC. 19/87

Additions made to sample: Atm.: H.P. Ar (gettered)

100g as-received + 7.87 g Fe₂O₃ + 0.94 g Fe powder

Total wt. of sample: 108.81 g Total wt. w/crucible: init.- 157.85 g
finl.- 157.67 g

RUN#: 3 TEMPERATURE: 1300°C ± 5°

SCALE (ohm)	DIAL READING	SLAG DEPTH (mm)	RESISTANCE (ohms)
3	127	0.0	1.95
1	88	4.95	0.78
1	68	7.49	0.61
1	48	10.03	0.51
1	38	11.3	0.47
1	28	12.57	0.44
1	18	13.84	0.40
1	08	15.11	0.375
1	998	16.38	0.35
1	988	17.65	0.325
1	978	18.92	0.30
1	968	20.19	0.28
1 (0.3)	958	21.46	0.26 (0.285)
1 (0.3)	948	22.73	0.245 (0.267)
1 (0.3)	938	24.0	0.23 (0.25)
1 (0.3)	928	25.27	0.21 (0.232)
1 (0.3)	918	26.54	0.19 (0.215)
1 (0.3)	908	27.81	0.16 (0.187)
1 (0.3)	899 BOTTOM	~~29.08~~	0.08 (0.11)
		Depth. 28.9 mm	

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.}$ = 0.08 Ω RUN#: 3

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	———	1.95	———
4.95	———	0.78	———
7.49	———	0.61	———
10.03	0.305	0.51	0.709
11.3	0.284	0.47	0.728
12.57	0.265	0.44	0.736
13.84	0.247	0.40	0.772
15.11	0.230	0.375	0.780
16.38	0.214	0.35	0.793
17.65	0.199	0.325	0.812
18.92	0.186	0.30	0.845
20.19	0.174	0.28	0.870
21.46	0.164	0.26	0.911
22.73	0.154	0.245	0.933
24.0	0.146	0.23	0.973
25.27	0.139	0.21	1.069.
26.54	———	0.19	———
27.81	———	0.16	———
29.08	———	———	———

wide - 0.832 ± 0.081

narrow - 0.906 ± 0.051

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 19/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5wt.% Fe_2O_3

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.(#1+2)
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.8	1.92	1.95	1.860
4.95	0.73	0.77	0.78	0.750
7.49	0.57	0.60	0.61	0.585
10.03	0.465	0.50	0.51	0.483
11.3	0.43	0.46	0.47	0.445
12.57	0.405	0.425	0.44	0.415
13.84	0.38	0.395	0.40	0.388
15.11	0.35	0.365	0.375	0.358
16.38	0.33	0.34	0.35	0.335
17.65	0.30	0.315	0.325	0.308
18.92	0.28	0.295	0.30	0.288
20.19	0.265	0.275	0.28	0.270
21.46	0.25	0.26	0.26	0.255
22.73	0.23	0.24	0.245	0.235
24.0	0.21	0.22	0.23	0.215
25.27	0.195	0.20	0.21	0.198
26.54	0.175	0.18	0.19	0.178
27.81	0.140	0.16	0.16	0.150
~~29.08~~	Rext. 0.07 —	Rext 0.08 —	Rext 0.08 —	0.075

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: HP. Ar

TEMPERATURE: 1300°C ± 5°

$r_{ext.} = 0.075\,\Omega$

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm) (#1+2)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.860	—
4.95	—	0.750	—
7.49	—	0.585	—
10.03	0.305	0.483	0.748
11.3	0.284	0.445	0.768
12.57	0.265	0.415	0.779
13.84	0.247	0.388	0.789
15.11	0.230	0.358	0.813
16.38	0.214	0.335	0.823
17.65	0.199	0.308	0.854
18.92	0.186	0.288	0.873
20.19	0.174	0.270	0.892
21.46	0.164	0.255	0.911
22.73	0.154	0.235	0.963
24.0	0.146	0.215	1.043
25.27	0.139	0.198	1.130
26.54	—	0.178	—
27.81	—	0.150	—
29.08	—	—	—

wide - 0.864 ± 0.084

narrow - 0.936 ± 0.068

SLAG CONDUCTIVITY DETERMINATION

DATE: DEC. 19/87

SUMMARY OF RESISTANCE MEASUREMENTS:

Atm.: H.P. Ar (gettered)

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3

TEMPERATURE: 1300°C ± 5°

DEPTH (mm)	RESISTANCE (ohms)			AVG.
	RUN# 1	RUN# 2	RUN# 3	
0.0	1.8	1.92	1.95	1.89
4.95	0.73	0.77	0.78	0.76
7.49	0.57	0.60	0.61	0.593
10.03	0.465	0.50	0.51	0.492
11.3	0.43	0.46	0.47	0.453
12.57	0.405	0.425	0.44	0.423
13.84	0.38	0.395	0.40	0.392
15.11	0.35	0.365	0.375	0.363
16.38	0.33	0.34	0.35	0.340
17.65	0.30	0.315	0.325	0.313
18.92	0.28	0.295	0.30	0.292
20.19	0.265	0.275	0.28	0.273
21.46	0.25	0.26	0.26	0.257
22.73	0.23	0.24	0.245	0.238
24.0	0.21	0.22	0.23	0.220
25.27	0.195	0.20	0.21	0.202
26.54	0.175	0.18	0.19	0.182
27.81	0.140	0.16	0.16	0.153
~~29.08~~	Rext. 0.07	Rext. 0.08	Rext. 0.08	Rext. 0.08

SLAG CONDUCTIVITY DETERMINATION

CONDUCTIVITY CALCULATION:

DATE: DEC. 19/87

SLAG SAMPLE: L05 Fe/SiO_2 with 5wt.% Fe_2O_3

Atm.: H.P. Ar (gettered)

TEMPERATURE: 1300 °C ± 5°

$r_{ext.}$ = 0.08 Ω

DEPTH (mm)	CELL CONSTANT (cm^{-1})	RESISTANCE (ohm)	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$)
0.0	—	1.89	—
4.95	—	0.76	—
7.49	—	0.593	—
10.03	0.305	0.492	0.740
11.3	0.284	0.453	0.761
12.57	0.265	0.423	0.773
13.84	0.247	0.392	0.792
15.11	0.230	0.363	0.813
16.38	0.214	0.340	0.823
17.65	0.199	0.313	0.854
18.92	0.186	0.292	0.877
20.19	0.174	0.273	0.902
21.46	0.164	0.257	0.927
22.73	0.154	0.238	0.975
24.0	0.146	0.220	1.043
25.27	0.139	0.202	1.139
26.54	—	0.182	—
27.81	—	0.153	—
29.08	—	—	—

wide - 0.867 ± 0.088

narrow - 0.891 ± 0.044.

APPENDIX II

CALCULATED ELECTRICAL CONDUCTIVITY VALUES FOR ALL SAMPLES

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 3/87

SLAG SAMPLE: 0.85 Fe/SiO_2 Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 104.57

100g as-received + 4.57g SiO_2

Total wt. w/crucible: init.- 151.50 g Weight change: 0.06 g
finl.- 151.44 Depth of Slag: 29.0 mm

TEMP. (°C)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°C ± 5°	1	0.357 ± 0.012	0.358 ± 0.003
"	2	0.370 ± 0.010	0.368 ± 0.004
"	3	0.371 ± 0.009	0.371 ± 0.002
"	2 and 3	0.370 ± 0.010	0.369 ± 0.003 *
1300°C ± 5°	1	0.436 ± 0.017	0.437 ± 0.012
"	2	0.441 ± 0.010	0.444 ± 0.002
"	3	0.442 ± 0.013	0.443 ± 0.002
"	2 and 3	0.442 ± 0.011	0.443 ± 0.0016 *

*Wide Range - all points considered except extremes
**Narrow - points within approx. 5mm below midpoint of melt considered

- temp. probably too low for first run [illegible] temp.
due to time taken to find the surface.

Analysis: Fe/SiO_2 = 0.843
Total CaO = 2.04 wt.%

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 6/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% Fe_2O_3 addition Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 109.80g

100g as-received + 4.57 SiO_2 + 5.23g Fe_2O_3

Total wt. w/crucible: init.- 159.51g Weight change: 0.17g

finl.- 159.34 Depth of Slag: 30.35 mm.

TEMP. (°C)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°C ± 5°	1	0.555 ± 0.019	0.558 ± 0.006
"	2	0.551 ± 0.018	0.554 ± 0.004
"	3	0.535 ± 0.015	0.536 ± 0.007
"	1 and 2	0.552 ± 0.017	0.556 ± 0.005 *
1300°C ± 5°	1	0.722 ± 0.050	0.723 ± 0.013
"	2	0.698 ± 0.048	0.701 ± 0.020
"	3	0.660 ± 0.030	0.658 ± 0.010
"	1 and 2	0.708 ± 0.048	0.710 ± 0.013 *

*Wide Range - all points considered except extremes

**Narrow - points within approx. 5mm below midpoint of melt considered

– third run (#3) at both temperatures [illegible] significantly lower than other runs. this might be due to [illegible] made at too low a temp than [illegible] expected – not [illegible] this [illegible] for more to [illegible].

Analysis : Fe/SiO_2 = 0.937

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 8/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 5 wt.% CaO addition Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 109.80 g

100 g as-received + 4.57 g SiO_2 + 5.23 g CaO

Total wt. w/crucible: init.- 159.91 g Weight change: 0.33 g

finl.- 159.58 Depth of Slag: 30.35 mm

TEMP. (°C)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°c ± 5°	1	0.400 ± 0.014	0.401 ± 0.005
"	2	0.406 ± 0.016	0.407 ± 0.005
"	3	0.395 ± 0.014	0.397 ± 0.005
"	all	0.400 ± 0.014	0.402 ± 0.005 *
1300°c ± 5°	1	0.485 ± 0.017	0.498 ± 0.008
"	2	0.471 ± 0.013	0.481 ± 0.004
"	3	0.530 ± 0.033	0.559 ± 0.019
"	1 and 2	0.477 ± 0.014	0.489 ± 0.006 *

*Wide Range - all points considered except extremes
**Narrow - points within approx. 5mm below midpoint of melt considered

- run #3 at 1300°c significantly higher than other two runs - disregarded

Analysis: Fe/SiO_2 = 0.838

CaO addition = 3.88 wt %

Total CaO = 6.0 wt.%

X

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 20/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 10 wt.% CaO addition Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 103.11g

90g as-received + 4.11g SiO_2 + 9.0g CaO

Total wt. w/crucible: init.- 152.47g Weight change: 0.93g

finl.- 151.54 Depth of Slag: 28.7 mm

TEMP. (^{o}C)	RUN(S) involved	CONDUCTIVITY (ohm^{-1}.cm^{-1}) Wide Range*	CONDUCTIVITY (ohm^{-1}.cm^{-1}) Narrow Range**
1250°C ± 5°	1	0.443 ± 0.006	0.442 ± 0.0008
"	2	0.461 ± 0.012	0.458 ± 0.008
"	3	0.423 ± 0.006	0.425 ± 0.002
"	all	0.442 ± 0.007	0.442 ± 0.002 *
1300°C ± 5°	1	0.544 ± 0.013	0.546 ± 0.0017
"	2	0.502 ± 0.008	0.498 ± 0.006
"	3	0.498 ± 0.006	0.495 ± 0.006
"	2 and 3	0.500 ± 0.006	0.496 ± 0.004 *

*Wide Range - all points considered except extremes

**Narrow - points within approx. 5mm below midpoint of melt considered

Analysis: Fe/SiO_2 = 0.843

CaO addition = 6.18 wt.%

Total CaO = 8.3 wt.%

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 21/87

SLAG SAMPLE: 0.85 Fe/SiO_2 with 15 wt.% CaO addition Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 108.23g

90g as-received + 4.11g SiO_2 + 14.12g CaO

Total wt. w/crucible: init.- 155.38 g Weight change: 1.54g

finl.- 153.84 Depth of Slag: 29.8mm

TEMP. (°C)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°C ± 5°	1	0.421 ± 0.004	0.423 ± 0.002
"	2	0.412 ± 0.004	0.414 ± 0.003
"	3	0.432 ± 0.006	0.431 ± 0.005
"	all	0.421 ± 0.003	0.423 ± 0.003 *
1300°C ± 5°	1	0.517 ± 0.004	0.515 ± 0.004
"	2	0.511 ± 0.007	0.514 ± 0.004
"	3	0.502 ± 0.006	0.503 ± 0.003
"	1 and 2	0.514 ± 0.005	0.514 ± 0.004. *

*Wide Range - all points considered except extremes

**Narrow - points within approx. 5mm below midpoint of melt considered

Analysis: Fe/SiO_2 = 0.845

CaO addition = 8.58 wt.%

Total CaO = 10.7 wt.%

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 9/87

SLAG SAMPLE: 0.95 Fe/SiO_2 Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 100.13g

100 g as-received + 0.13g SiO_2

Total wt. w/crucible: init.- 147.53 g Weight change: 0.04 g
finl.- 147.49 Depth of Slag: 26.5 mm

TEMP. (°C)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°C ± 5°	1	0.530 ± 0.004 – too deep.	0.533 ± 0.002
"	2	0.513 ± 0.011	0.509 ± 0.005
"	3	0.489 ± 0.008	0.487 ± 0.002
"	2 and 3	0.500 ± 0.009	0.497 ± 0.002 *
1300°C ± 5°	1	0.602 ± 0.015	0.603 ± 0.007
"	2	0.585 ± 0.016	0.589 ± 0.006
"	3	0.597 ± 0.015	0.603 ± 0.007
"	1 and 3.	0.599 ± 0.014	0.603 ± 0.006. *

*Wide Range - all points considered except extremes
**Narrow - points within approx. 5mm below midpoint of melt considered

Analysis: Fe/SiO_2 = 0.940

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 11/87

SLAG SAMPLE: 0.95 Fe/SiO_2 with 5wt.% Fe_2O_3 addition Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 105.13g

100g as-received + 0.13g SiO_2 + 5.0g Fe_2O_3

Total wt. w/crucible: init.- 156.10 g Weight change: 0.15g
fin1.- 155.95 Depth of Slag: 28.3 mm

TEMP. (^{o}C)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°C ± 5°	1	0.744 ± 0.077	0.709 ± 0.026
"	2	0.693 ± 0.060	0.666 ± 0.015
"	3	0.693 ± 0.061	0.669 ± 0.022
"	2 and 3	0.693 ± 0.061	0.667 ± 0.018 *
1300°C ± 5°	1	0.805 ± 0.077	0.827 ± 0.057
"	2	0.769 ± 0.052	0.794 ± 0.033
"	3	0.801 ± 0.083	0.831 ± 0.056.
"	1 and 3	0.802 ± 0.080	0.828 ± 0.056 *

*Wide Range - all points considered except extremes
**Narrow - points within approx. 5mm below midpoint of melt considered

Analysis: Fe/SiO_2 = 1.029

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 17/87

SLAG SAMPLE: 1.05 Fe/SiO_2 (actually 1.029 Fe/SiO_2) Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 103.63 g

100g as-received + 2.69 g Fe_2O_3 + 0.94 g Fe powder

Total wt. w/crucible: init.- 152.82 g
finl.- 152.72

Weight change: 0.10 g
Depth of Slag: ~27.5 mm

TEMP. (°C)	RUN(S) involved	CONDUCTIVITY (ohm^{-1}.cm^{-1}) Wide Range*	CONDUCTIVITY (ohm^{-1}.cm^{-1}) Narrow Range**
1250°C ± 5°	1	0.542 ± 0.031	0.552 ± 0.021
"	2	0.534 ± 0.032	0.541 ± 0.018
"	3	0.508 ± 0.023	0.513 ± 0.013
"	1 and 2	0.537 ± 0.032	0.546 ± 0.020 *
1300°C ± 5°	1	0.736 ± 0.055	0.715 ± 0.021
"	2	0.742 ± 0.085	0.709 ± 0.029
"	3	0.765 ± 0.102	0.723 ± 0.027
"	1 and 2	0.738 ± 0.069	0.712 ± 0.025 *

*Wide Range - all points considered except extremes
**Narrow - points within approx. 5mm below midpoint of melt considered

Analysis: Fe/SiO_2 = 1.015

X

SLAG CONDUCTIVITY DETERMINATION:

SUMMARY OF CONDUCTIVITY VALUES: DATE: DEC. 19/87

SLAG SAMPLE: 1.05 Fe/SiO_2 with 5 wt.% Fe_2O_3 addition (actually 1.029 Fe/SiO_2) Atm.: HP. Ar

Additions made to sample: Total wt. of sample : 108.81g

100g as-received + 7.87g Fe_2O_3 + 0.94g Fe powder

Total wt. w/crucible: init.- 157.85 g Weight change: 0.18g

finl.- 157.67g Depth of Slag: ~28.5g

TEMP. (^oC)	RUN(S) involved	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Wide Range*	CONDUCTIVITY ($ohm^{-1}.cm^{-1}$) Narrow Range**
1250°C ± 5°	1	0.795 ± 0.073	0.765 ± 0.022
"	2	0.760 ± 0.056	0.742 ± 0.022
"	3	0.763 ± 0.071	0.732 ± 0.020
"	2 and 3	0.761 ± 0.063	0.736 ± 0.020 *
1300°C ± 5°	1	0.871 ± 0.080	0.939 ± 0.066
"	2	0.859 ± 0.089	0.935 ± 0.070
"	3	0.832 ± 0.081	0.906 ± 0.051
"	1 and 2	0.864 ± 0.084	0.936 ± 0.068 *

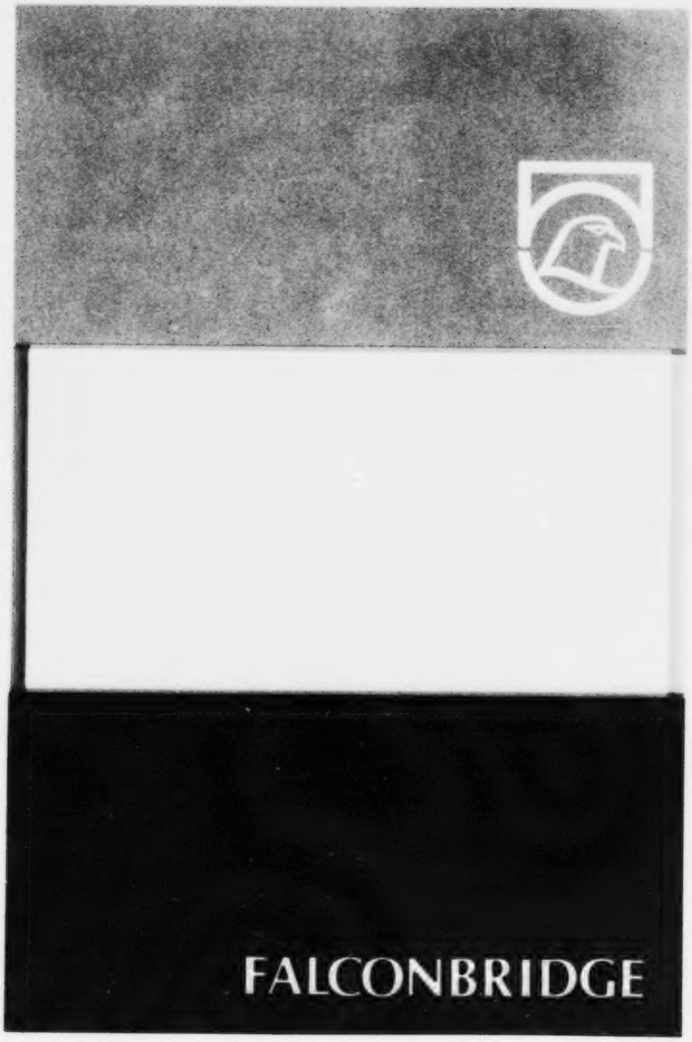
*Wide Range - all points considered except extremes

**Narrow - points within approx. 5mm below midpoint of melt considered

Analysis: Fe/SiO_2 = 1.099

Volume

5



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TO DEVELOP A CLEAN SMELTING PROCESS FOR HIGHLY ROASTED COPPER-NICKEL CALCINES AND TO IMPROVE METAL RECOVERY

PART E:

FINAL REPORT

(SUMMARY OF PARTS A THROUGH D)

by

N. M. Stubina and G. H. Kaiura

Work on the project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources Canada

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TABLE OF CONTENTS

PAGE

EXECUTIVE SUMMARY 1

SOMMAIRE 3

INTRODUCTION 6

THERMOGRAVIMETRIC-GAS CHROMATOGRAPHIC ANALYSIS OF SMELTING 6

DENSITIES OF MOLTEN COPPER-NICKEL MATTES 10

METALLIC PHASE SATURATION BOUNDARY IN THE Ni-Cu-Fe-S SYSTEM BETWEEN 1000 AND 1300°C 14

ELECTRICAL CONDUCTIVITY MEASUREMENTS OF ELECTRIC FURNACE SMELTING SLAGS 15

REFERENCES 22

EXECUTIVE SUMMARY

In order to meet environmental requirements and to cut operating costs, a new smelting process was commissioned for Falconbridge Limited's Sudbury Operation in 1978. The current process consists of two fluid bed roasters, two electric furnaces, a converter aisle, and an acid plant. The new smelter was designed to operate at a roaster sulphur elimination of 50%; this has recently been increased to 60%. Increasing the degree of roast even further would give an additional decrease in sulphur dioxide emissions by increasing the fraction converted to sulphuric acid.

When the degree of roast is increased, however, more heavily oxidized calcines are produced. This results in higher matte grades in the electric furnace which are detrimental to smelter metal recoveries. The countermeasure is to smelt under more intensive reducing conditions. In the presence of coke a dense metallic phase forms during the smelting of the calcine. This leads to a buildup of metal on the furnace hearth, thus, reducing the capacity of the furnace and interfering with the tapping operation.

In order to develop and implement the proposed "clean smelting" regime, there must be a clear understanding of the processes that take place in the charge to the electric furnace, the behaviour of coke in the reduction process, and the properties of the matte and slag present in the furnace. This contract was divided into four distinct sections:

1. Thermogravimetric-Gas Chromatographic Analysis of Smelting
2. Matte Density Studies
3. Metallic Phase Saturation Boundary, and
4. Physical Properties of Smelting Slags (Electrical Conductivity of Slags).

The data generated from this work will enable Falconbridge Limited to:

1. increase sulphur dioxide recovery and reduce sulphur dioxide emissions,
2. improve recoveries of nickel and cobalt, and
3. maintain a continuous and reliable electric furnace operation.

In the first part of the contract, a thermogravimetric analyzer - gas chromatograph combination was used to examine the behaviour of electric furnace feed mixtures (i.e. calcine and coke). The sample heating rate was selected to reflect the residence time in the smelting furnace. As the temperature was increased, specific reactions that occurred were identified according to temperature of occurrence, quantity reacted, rate of reaction, and composition of the gaseous products. Additional samples were examined by arresting the process at various temperatures. The condensed phase composition was determined by chemical analysis and sections were examined metallographically and with electron-probe micro-analysis. The data from this testwork, in conjunction with fundamental thermodynamic principles, were applied in order to determine the sequence of chemical reactions encountered in a unit of charge as it descends from the freeboard to the liquid slag. Heating by slag resistance in an electric smelting furnace establishes a natural temperature gradient, from approximately 500°C near the freeboard to 1230°C at the slag level. The low temperature reactions occur partly in contact with ingress air, and the high temperature reactions occur at a greater depth within the bed where the oxygen supply is limited by both the need for diffusion into the charge layer and the increasing reactivity of coke at higher temperatures. The effect of different levels of coke and lime additions on the smelting process were also examined.

In the second part of the contract, a bottom-weighing Archimedean technique was used to determine the densities of twenty different copper-nickel mattes. The copper to nickel mass ratios were fixed at 1:1 and the matte grades were varied between 13 and 57%. The iron to oxygen mass ratios of the mattes were approximately 16:1, which is typical of industrial mattes. Density measurements were determined in the 1100-1300°C temperature range. Industrially, density data are important for a variety of reasons. Density data are required in the analyses of reaction rates that occur in sulphide smelting and converting processes. For example, they can be used to establish the concentration of the melt in terms of unit volume. This can be used to formulate natural convective effects that arise from density changes resulting from metallurgical reactions. Knowledge of densities could also lead to a better understanding of the phenomenon that give rise to the presence of a solid magnetite phase in smelting and converting vessels.

The objective of the third part of the contract was to identify the restrictions placed on coke reduction because of metal precipitation in the matte. Over-reduction by coke results in the formation of excessive quantities of metal which precipitate from the matte phase. In the coke reduction zone, the appearance of the metallic phase fixes the thermodynamic conditions with respect to the oxygen potential of the system. This limit is critical to recovery because the nickel and cobalt losses in the slag are closely connected to the oxygen potential. In the bulk matte zone, metal precipitation causes hearth accretions which reduce the furnace capacity. A laboratory study was initiated in order to yield matte-metal equilibration data at temperatures ranging from 1000 to 1300°C. The compositions of the mattes (Ni-Cu-Fe-S-O) were in the range encountered in Falconbridge matte smelting utilizing increased degrees of roast. The effect of different Ni/Cu ratios on the experimental results were also examined.

The electrical conductivities of smelting slags were determined in the fourth part of the contract. A laboratory-scale crucible-probe conductivity cell was used for the determinations. The parameters investigated include: temperature, Fe/SiO_2 ratio, lime content, and Fe_2O_3 additions to the slag. These parameters were varied over the range applicable to electric furnace smelting at increased coke rates. From an industrial perspective, electrical conductivities are needed in order to predict electric furnace behaviour as the slag chemistry is altered.

SOMMAIRE

Afin de répondre aux exigeances environnementales et de réduire les coûts d'exploitation, un nouveau procédé de fusion a été commandé en 1978 pour l'installation de Sudbury de la compagnie Falconbridge Limited. Le procédé actuel comporte deux fours à lit fluidisé, deux fours électriques, un convertisseur et une usine de fabrication d'acide. La nouvelle fonderie a été conçue pour supprimer 50% du soufre dans les fours de grillage; ce chiffre a récemment été augmenté à 60%. Un deuxième augmentation de l'intensité de grillage réduirait davantage les émissions de bioxide de soufre en raison de l'augmentation de la proportion convertie en acide sulfurique.

Mais l'augmentation de l'intensité de grillage produit des concentrés calcinés plus oxydés donnant lieu à des mattes de teneur plus élevée dans le four électrique. Ceci agit au détriment du rendement métal de la fonderie. La contre-mesure consiste en la fusion de minerais dans des conditions plus intensives de réduction. En présence du coke, toutefois, il se forme une phase métallique dense lors de la fusion du calciné, ce qui cause une accumulation de métal au sole du four diminuant la capacité du four et nuisant à la coulée.

Afin de mettre au point et de mettre en pratique le régime de "fonte salubre" envisagé, il est nécessaire de bien comprendre d'abord l'action qui se poursuit dans la charge du four électrique; puis le comportement du coke lors du processus de réduction et enfin les propriétés de la matte et de la scorie qui sont présentes dans le four. Le contrat a été divisé en quatre parties distinctes:

1. l'analyse de la fusion à partir d'une combinaison de thermogravimétrie et de chromatographie en phase gazeuse;
2. les études sur la densite de mattes;
3. la détermination du seuil de saturation de la phase métallique;
4. l'étude des propriétés physiques des scories de fonte (conductivité électrique des scories).

Les données obtenues lors de ces travaux permettront à la compagnie Falconbridge Limited de:

1. augmenter le taux de récupération de bioxide de soufre et d'en réduire la quantité émise dans l'atmosphère;
2. améliorer la quantité récupérée de nickel et de cobalt;
3. maintenir un fonctionnement continu et efficace des fours électriques.

Lors de la première partie du contrat, une combinaison de thermogravimétrie et de chromatographie en phase gazeuse a été utilisée pour étudier le comportement des mélanges concentrés destinés au four électrique (c-à-d les calcinés et le coke). Le degré de chauffage de l'échantillon a été choisi en fonction de la durée du traitement métallurgique dans le four de fusion. A mesure que la

température a été augmentée, les réactions ayant lieu ont été précisées selon la température à laquelle elles se produisaient, la quantité participant a la réaction, la vitesse de réaction et la composition des gazs qui en résultaient. D'autres échantillons ont été examinés en arrêtant le processus à des températures données. La composition des phases condensées a été déterminée au moyen d'analyses chimiques et certaines sections ont fait l'objet d'un examen métallographique et d'une micro-analyse avec sonde électro-métrique. Les données obtenues lors de ces travaux d'essai ainsi que les principes fondamentaux de thermodynamique ont été utilisés afin de déterminer l'ordre des réactions chimiques qui se produisent au sein d'une charge donnée au cours de sa progression du franc-bord jusqu'à la scorie liquide. Le chauffage utilisant la résistance de la scorie d'un four électrique produit une progression naturelle de températures allant d'environ 500°C près du franc-bord jusqu'à 1230°C au niveau de la scorie. Les réactions à basse température se produisent partiellement au contact de l'air et les réactions à haute température se réalisent à une plus grande profondeur dans le lit du four où la quantité d'oxygène est restreinte. Cette restriction est causée, d'une part, par la diffusion obligatoire de l'oxygène dans la couche de la charge, et, d'autre part, par la plus grande réactivité du coke à des température plus élevées. Les effets de différentes quantités de coke et de chaux sur le processus de la fusion ont aussi été examinés.

Lors de la deuxième partie du contrat, la densité de vingt différents échantillons de mattes de cuivre-nickel a été déterminée par l'application du principe d'Archimède à un système de pesage par en bas. Les proportions par masse de cuivre/nickel étaient égales (1:1) tandis que celles de fer/oxygène étaient d'environ 16:1, ce qui est typique des mattes industrielles. La qualité de la matte variait de 13% a 57%. Les mesures de densité ont été déterminées à des températures allant de 1100°C à 1300°C. Ces données jouent un rôle important dans une perspective industrielle pour plusieurs raisons. Premièrement, les données de densité sont nécessaires aux analyses de la rapidité des réactions qui se produisent lors de la fusion des sulfures et du processus de conversion. Par exemple, elles peuvent être utilisées pour établir la concentration de la fonte exprimée en fonction d'unité de volume. Ce chiffre peut ensuite servir à calculer les effets de la convection naturelle lors des changements de densité causés par les réactions métallurgiques. Deuxièmement, la connaissance des densités peut mener à une meilleure compréhension des phénomènes qui provoquent la formation d'une phase de magnétite solide dans les récipients de fusion et de conversion.

Le but de la troisième partie du contrat a été de repérer les restrictions apportées au degré de réduction du coke en raison de la précipitation de métaux dans la matte. La sur-réduction du coke résulte en la formation de quantités excessives de métaux qui se précipitent de la matte. Dans la zone de réduction du coke, la manifestation de la phase métallique fixe les conditions thermodynamiques par rapport au potentiel en oxygene du système. Cette limite est cruciale au rendement puisque les pertes de nickel et de cobalt dans les scorie sont étroitement liées au potentiel en oxygène. Dans la zone de mattes en vrac, les précipitations de métaux causent des accumulations au sole qui réduisent la capacité du four. Une étude en laboratoire a été effectuée afin de déterminer les données des matte-métaux équilibrées à des températures de 1000 à 1300°C. Les compositions des mattes (Ni, Cu, Fe, S, O) se situaient dans les limites obtenues lors de la fusion de mattes à des températures plus élevées de grillage à l'usine de Falconbridge. De plus, les effets de différents rapports nickel/cuivre sur les données expérimentales ont été examinés.

La conductivité des scories de fusion a été déterminée lors de quatrième partie du contrat. Pour ce faire, une cellule conductive en forme de creuset-sonde fabriquée de molybdène et qui était de grandeur laboratoire a été utilisée. Les paramètres étudiés étaient les suivants: le rapport de Fe/SiO_2, la quantité de chaux et les additions de Fe_2O_3 à la scorie. Ces paramètres se situent dans la limite applicable à la fusion dans un four électrique utilisant des quantités plus importantes de coke. Dans une perspective industrielle, les données de conductivité électrique sont nécessaires afin de prédir le fonctionnement des fours électriques à mesure que change la composition chimique de la scorie.

INTRODUCTION

Due to environmental and economic considerations, a new smelting process was commissioned for Falconbridge Limited's Sudbury Operation in 1978. The current process consists of two fluid bed roasters, two electric furnaces, a converter aisle, and an acid plant. The new smelter was designed to operate at a roaster sulphur elimination of 50%. Recently, this value has been increased to 60%. Operating at even higher degrees of roast is attractive as a means of improving the control of sulphur distribution in the plant. This advantage must be weighed against the possibility of higher metal loss to the electric furnace slag phase. Before the 'clean smelting' regime can be implemented there must be a clear understanding of the processes that take place in the charge to the electric furnace, the behaviour of coke in the reduction process, and the properties of the matte and slag present in the furnace. This contract was divided into four distinct sections:

1. Thermogravimetric-Gas Chromatographic Analysis of Smelting
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The data generated from this work will enable Falconbridge Limited to:

1. increase sulphur dioxide recovery and reduce sulphur dioxide emissions,
2. improve recoveries of nickel and cobalt, and
3. maintain a continuous and reliable electric furnace operation.

The four sections are summarized below.

THERMOGRAVIMETRIC-GAS CHROMATOGRAPHIC ANALYSIS OF SMELTING

In the electric furnace, the smelting of calcine occurs in a series of stages:

1. heating of the charge (up to 950°C);
2. sulphide fusion and reduction by coke (950-1150°C);
3. matte-slag separation by settling (1150-1250°C);
4. recycle converter slag reduction (1200°C) and
5. matte accumulation in the hearth (1100°C).

In this part of the contract, the first two stages of smelting were investigated. In particular the sequence of reactions and the gaseous products evolved were determined. For this purpose four variables were assigned, namely:

1. degree of sulphur elimination from the calcine (50-75%);
2. coke addition (0-5%);
3. gas atmosphere (nitrogen and air) and
4. lime addition (0-15%).

The behaviour of calcine mixtures was studied during heating by a thermogravimetric analyzer-gas chromatograph combination. This method provides a correlation of mass changes and gas compositions with temperature. Chemical reactions are identified according to the temperature range of occurrence, reaction rate, and extent. As this method alone does not positively identify all chemical reactions, other techniques were employed in order to obtain more comprehensive data. During several tests the heating was arrested and the samples were examined by optical, chemical, micrographic, or electron microprobe analysis.

The sequence of smelting reactions that occur in the electric furnace can be classified according to the temperature range of occurrence as shown in Figure 1 (N_2 atmosphere-with and without lime addition) and in Figure 2(air atmosphere). Many similar reactions proceed under both oxidizing and neutral conditions, but if a supply of gaseous oxygen is available then the air-charge interaction becomes the dominant feature of the system. The important high temperature smelting reactions occur in the absence of air. These consist primarily of rapid oxide reduction by coke and secondarily, reduction by iron sulphide. The addition of lime to the system eliminated SO_2 discharge by stabilizing the sulphur as $CaSO_4$ or CaS.

The tests using nitrogen more closely represent the sequence in the electric furnace because oxygen supply in the calcine layer is restricted by the need for gas diffusion downwards against the rising stream of CO and CO_2 from the fusion zone. Figure 1 represents a graphic display of reactions that occur within a vertical section of the charge layer in an electric furnace. This can be visualized as a series of reaction zones encountered by a unit of charge as it descends from the freeboard to the slag.

To obtain high pay-metal recoveries during the smelting of highly roasted concentrates it is necessary to maximize coke utilization. Coke burnoff by contact with ingress air diminishes reductant availability and may result in high furnace freeboard temperatures. Productive coke involvement in electric smelting is primarily in the matte-assisted reduction of oxides. These reactions are extremely rapid and are tolerant of different coke feeds. High temperature smelting reactions are limited by coke supply, up to the 5% addition level examined. Reductant consumption within this regime is complete and rapid.

Environmental considerations favour the elimination of sulphur from the concentrate prior to smelting. Two characteristics of highly roasted calcines have been identified: lower availability of sulphur and higher input of oxygen. Increased desulphurization is achieved by roasting at higher temperatures. High temperatures aid in depressing the formation of metal sulphates in the calcine. Sulphates contribute directly to SO_3 and SO_2 formation in the electric furnace by undergoing thermal decomposition. Any decrease in sulphate formation in the roasters is beneficial in terms of lower SO_2 formation and in lower oxygen input to smelting.

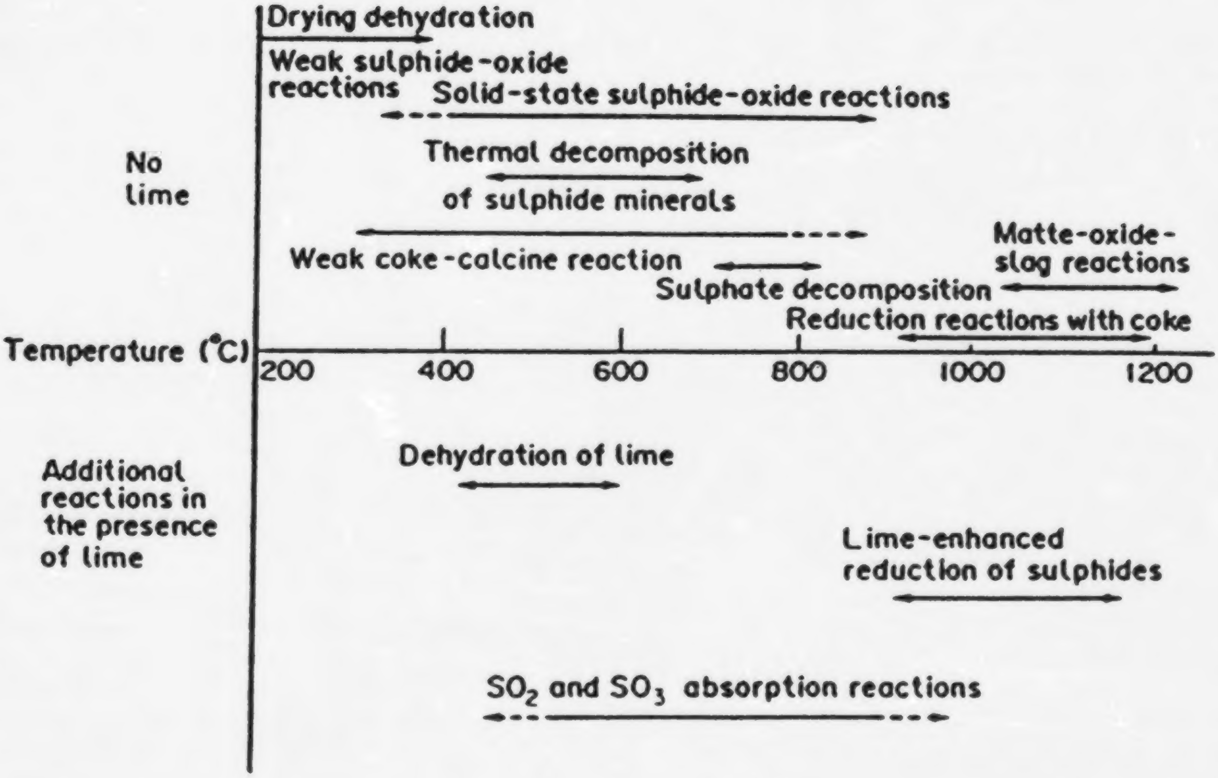
Drying dehydration
Weak sulphide-oxide reactions
Solid-state sulphide-oxide reactions
No lime
Thermal decomposition of sulphide minerals
Weak coke-calcine reaction
Matte-oxide-slag reactions
Sulphate decomposition
Reduction reactions with coke
Temperature (°C)
200
400
600
800
1000
1200
Additional reactions in the presence of lime
Dehydration of lime
Lime-enhanced reduction of sulphides
SO_2 and SO_3 absorption reactions

Figure 1. Smelting Reactions Under a Nitrogen Atmosphere

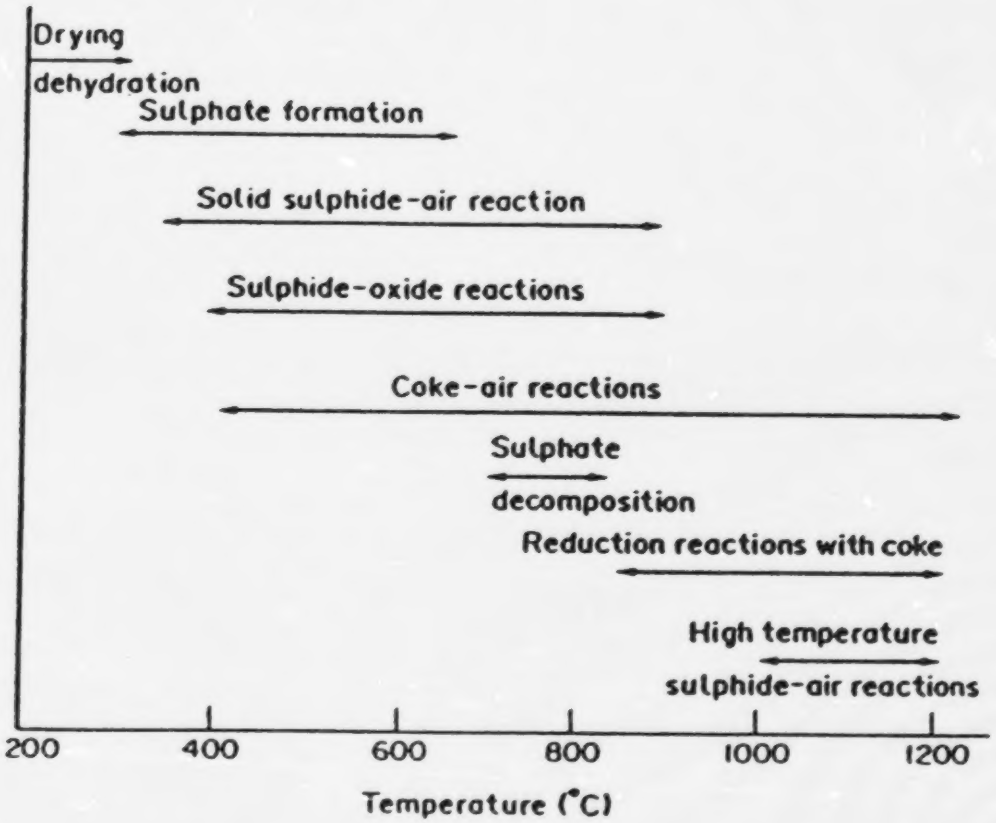

Figure 2. Smelting Reactions Under an Air Atmosphere

DENSITIES OF MOLTEN COPPER-NICKEL MATTES

Industrially, accurate density data are desired for a variety of reasons. In conventional copper-nickel converting, the quantity of matte being processed is usually recorded by the number of ladles handled. Although the volume of each ladle is known, the mass of matte in each ladle is usually estimated, since the density of the matte is unknown. Therefore, matte density data is required to improve the accuracy of material balances in the smelter. Also, density data leads to a better understanding of the phenomena which give rise to the presence of a solid magnetite phase in the smelting vessel. Density data are needed in order to estimate the time required for a matte droplet to settle from the slag phase. From a theoretical perspective, density data is useful in explaining the structure of sulphide melts.

The limited amount of density data for commercial Cu-Ni mattes is due to the numerous difficulties encountered when working with these types of systems. The more important of these are:

1. changes in specimen composition due to sulphur evolution from the matte, and

2. interfacial tension effects between the molten matte specimen and the density probes.

In this work, a bottom-weighing Archimedean technique, previously developed at the University of Toronto was used to measure the density of 20 different Cu-Ni mattes as a function of temperature and composition. This section of the contract was sub-contracted to the University of Toronto. This work is based on the Master of Applied Engineering thesis of Mr. J. Hryn.

The compositions of the matte specimens investigated are essentially in the five component Cu-Ni-Fe-S-O system. By setting the Cu/Ni mass ratio to unity and the Fe/O mass ratio to 16, the system is reduced to three components, which is more convenient to represent the density data. The Fe/O mass ratio of 16 is of particular interest to commercial smelting operations. Since some of the specimens were obtained from Falconbridge Limited, they contain a small amount of cobalt (a few tenths of a percent). With respect to the sulphur and oxygen in the mattes, cobalt behaves more like iron than either copper or nickel. Therefore, it was assumed that grouping the small amount of cobalt with the iron would not significantly affect the presentation of the results.

Figures 3 and 4 show typical density data obtained in this study. Based on a linear regression of the data, the density, standard error of estimate, the correlation coefficient ("R"), and the temperature coefficient ("Alpha") for each matte specimen are summarized in Table 1. Since the correlation coefficient is close to unity, it can be assumed that the density of each matte specimen varies almost linerarly with temperature.

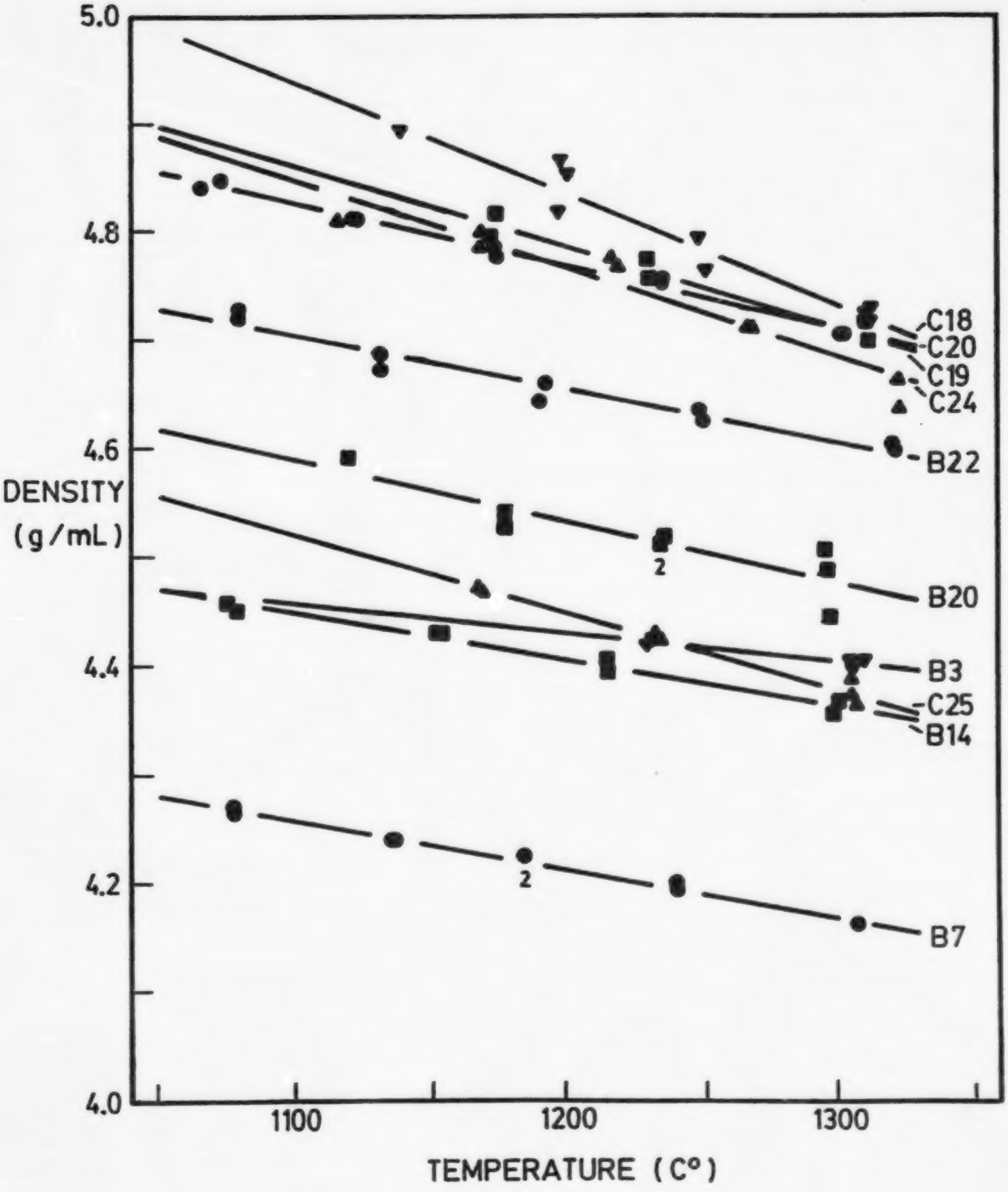

Figure 3. Density Data as a Function of Temperature

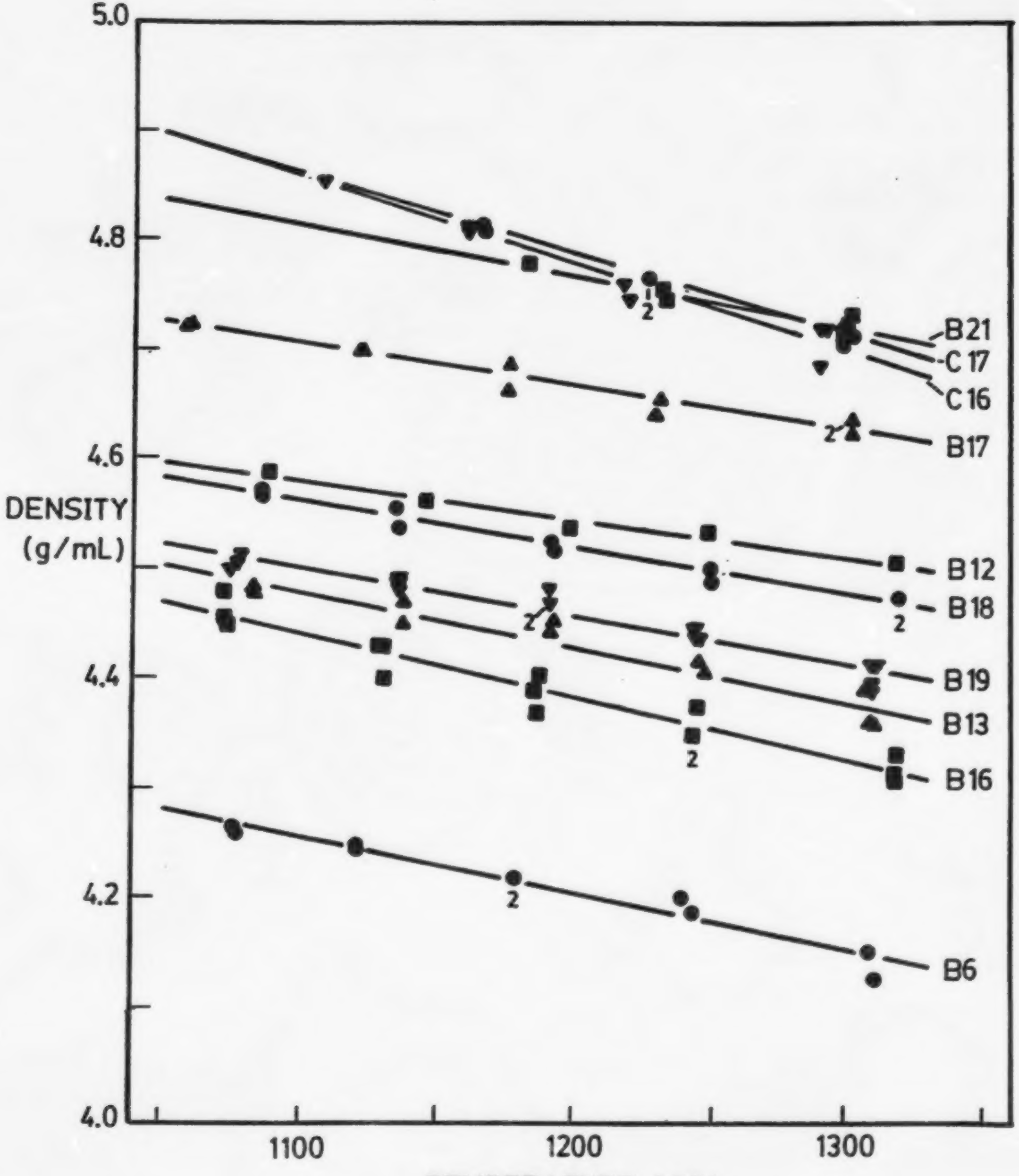

Figure 4. Density Data as a Function of Temperature

TABLE 1. Densities of the Matte Specimens

SPECIMEN NUMBER	DENSITY (g/mL) 1100°C	1200°C	1300°C	STD ERROR OF ESTIMATE (g/mL)	R	ALPHA x1000
B3	4.459	4.432	4.404	0.004	0.954	0.275
B6	4.258	4.207	4.155	0.010	0.979	0.512
B7	4.260	4.216	4.172	0.003	0.996	0.444
B12	4.580	4.546	4.512	0.005	0.988	0.340
B13	4.477	4.428	4.379	0.011	0.943	0.491
B14	4.450	4.407	4.364	0.007	0.987	0.426
B16	4.441	4.384	4.327	0.014	0.968	0.574
B17	4.706	4.668	4.629	0.008	0.977	0.385
B18	4.562	4.521	4.479	0.007	0.984	0.418
B19	4.503	4.459	4.414	0.010	0.970	0.444
B20	4.587	4.532	4.477	0.018	0.888	0.547
B21	4.814	4.768	4.723	0.008	0.948	0.454
B22	4.705	4.656	4.607	0.011	0.975	0.490
C16	4.861	4.787	4.714	0.005	0.995	0.737
C17	4.858	4.779	4.700	0.014	0.974	0.789
C18	4.941	4.838	4.736	0.016	0.973	1.028
C19	4.860	4.788	4.716	0.016	0.965	0.719
C20	4.827	4.770	4.712	0.005	0.996	0.576
C24	4.849	4.766	4.684	0.018	0.963	0.828
C25	4.520	4.451	4.382	0.006	0.992	0.690

Specimens received from Falconbridge Limited.

SPECIMEN NUMBER	COMPOSITIONS (mass %) Cu+Ni	Fe+O(+Co)	S	RATIOS Cu/Ni	Fe(+Co)/O
B3	35.9	35.8	28.3	1.02	18.9
B6	16.6	53.3	30.1	0.99	14.1
B7	20.3	51.9	27.8	0.98	14.4
B12	24.5	49.3	26.2	0.97	20.3
B13	26.6	45.7	27.7	0.98	18.2
B14	29.5	42.4	28.1	0.97	17.6
B16	33.1	38.2	28.7	0.99	17.8
B17	33.0	41.6	25.4	0.96	21.1
B18	35.2	37.3	27.5	0.97	19.1
B19	38.3	33.1	28.6	0.98	20.3
B20	15.7	58.8	25.5	0.94	16.6
B21	23.7	52.1	24.2	0.94	23.4
B22	28.1	46.4	25.5	0.99	21.1

Synthesized matte specimens.

SPECIMEN NUMBER	COMPOSITIONS (mass %) Cu+Ni	Fe+O	S	RATIOS Cu/Ni	Fe/O
C16	44.4	30.0	25.6	0.97	23.8
C17	46.8	27.3	25.9	1.01	18.7
C18	50.0	23.7	26.3	1.01	23.3
C19	53.3	20.0	26.7	0.98	32.7
C20	57.0	16.3	26.8	0.88	36.6
C24	29.6	46.8	23.6	1.01	25.9
C25	13.3	60.9	25.8	0.99	27.0

An examination of Table 1 reveals that the "Alpha" values (temperature coefficient of density) vary considerably over the range of composition investigated. The data do not indicate any significant correlation with either (%Cu +%Ni) or with %S. However, since the "Alpha" values are small, the relative errors associated with them are large. Nevertheless, "Alpha" is assumed to be independent of composition.

An overall empirical equation of density "D" (g/mL) as a function of sulphur content "S" (%S), matte grade "G" (Σ(%Cu + %NI)), and temperature "t" (^{o}C) has been determined to be:

$$D = 6.532 - 0.0856\ S + 0.0097\ G + 0.00049\ (12\overset{0}{\underset{\wedge}{0}}-t)$$

The standard deviation for this equation is 0.0496 g/mL.

The bottom-weighing technique used in this investigation offers many advantages over other techniques used to determine densities of molten sulphides. Problems associated with surface tension effects can be eliminated using the two-bob approach. Composition changes due to sulphur evolution can be detected because the specimen weight is continuously being monitored. Also, because the specimen and not the bob is being weighed, the bob density can be less than the specimen density, since the bob can be forced into the melt. Therefore, the bob material can be selected for its chemical inertness with respect to the specimen, and not for its particular density.

The largest sources of error in this study are chemical analyses of specimen compositions and measurement errors. With the present method, the expected accuracy of the data is better than +/- 0.5%. This value is primarily based on the precision to which the bob volume was determined during calibration, and the accuracy to which the weight of displaced matte can be measured during experimentation.

METALLIC PHASE SATURATION BOUNDARY IN THE Ni-Cu-Fe-S SYSTEM BETWEEN 1000 AND 1300^{o}C

As previously discussed, increasing the degree of roast is environmentally attractive because more of the sulphur in the concentrate can be fixed as sulphuric acid. When the degree of roast is increased, however, more heavily oxidized calcines are produced. This results in higher matte grades in the electric furnace which are detrimental to smelter metal recoveries. The countermeasure is to smelt under more intensive reducing conditions. In the presence of coke a dense metallic phase forms during the smelting of the calcine. This leads to a buildup of metal on the furnace hearth, thus, reducing the capacity of the furnace and interfering with the tapping operation.

This part of the contract was initiated in order to yield matte-metal equilibration data at temperatures ranging from 1000 to 1300°C. The compositions of the mattes (Ni, Cu, Fe, S) were in the range encountered in Falconbridge matte smelting utilizing increased degrees of roast. The tests were performed in sealed tubes and metallics were added in the form of a ferronickel alloy. The equilibration reaction between matte and metallics resulted in the formation of a new metallic phase in equilibrium with molten matte. The analysis of these mattes and the new metallic phases provided the data necessary to construct tie-lines between the two phases. Industrially, it is desirable to ascertain the location of the matte-metal saturation boundary. This boundary represents a condition of minimum oxygen potential at which point slag losses of nickel and cobalt are at their lowest.

Another objective was the estimation of the liquidus temperatures. This information is of value in predicting alloy formation at various temperatures as there is a vertical temperature gradient throughout the electric furnace.

Typical results obtained in this study are presented in Figures 5 and 6. Tie-lines are omitted from the diagrams for the sake of clarity. Results by Sobolev et al. are included for comparison purposes. As metal saturation is reached, a solid Fe-(Ni+Cu+Co) alloy precipitates. Further additions of coke results in an increase in the mass of metallics relative to liquid matte.

A schematic diagram illustrating the effects of coke additions and degrees of roast is shown in Figure 7. The composition of alloy in equilibrium with liquid matte traverses towards the Fe corner as the oxygen potential decreases. The alloy composition in equilibrium with liquid matte is a function of the oxygen potential of the system, which decreases with coke addition. At any metallics composition, the system oxygen potential is fixed by the matte-slag-alloy equilibrium; thus, the matte grade and oxygen solution capacity are also fixed. In the smelting furnace the metallized matte sinks down to the hearth, acting as a reductant for metal oxides recycled in converter slag.

The operation of commercial electric furnaces requires an efficient utilization of coke additions and the minimization of nickel losses to the slag. Accurate saturation boundary data are required for both of these purposes.

ELECTRICAL CONDUCTIVITY MEASUREMENTS OF ELECTRIC FURNACE SMELTING SLAGS

This section was subcontracted to the University of Toronto. The work was performed by M. H. Tseng under the auspices of Prof. J. M. Toguri.

The relationship between a slag's electrical conductance, composition and liquidus temperature is important from an industrial perspective. Electric furnace parameters and mode of furnace operation depend on the electrical conductivity of the slag.

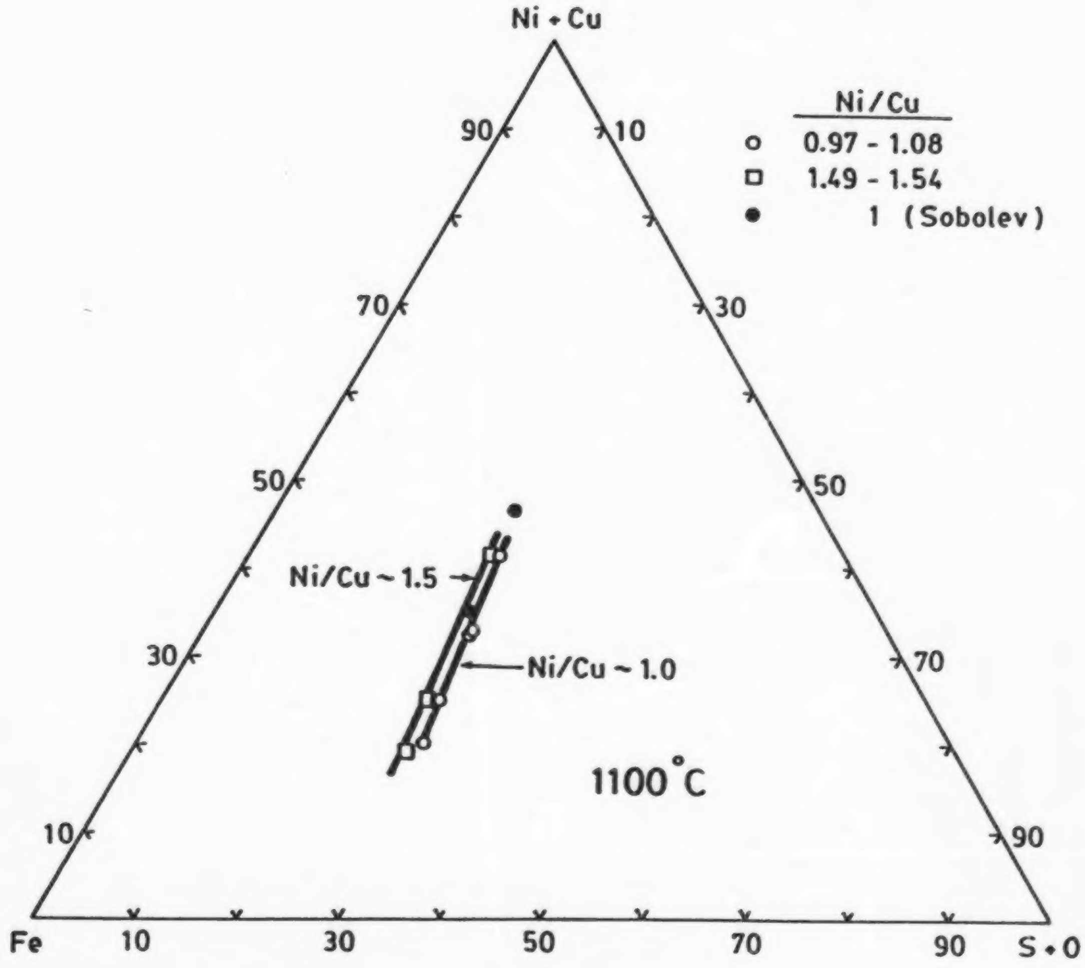

Figure 5. The Effect of the Ni/Cu Ratio on the Matte-Metal Saturation Boundary at 1100C.

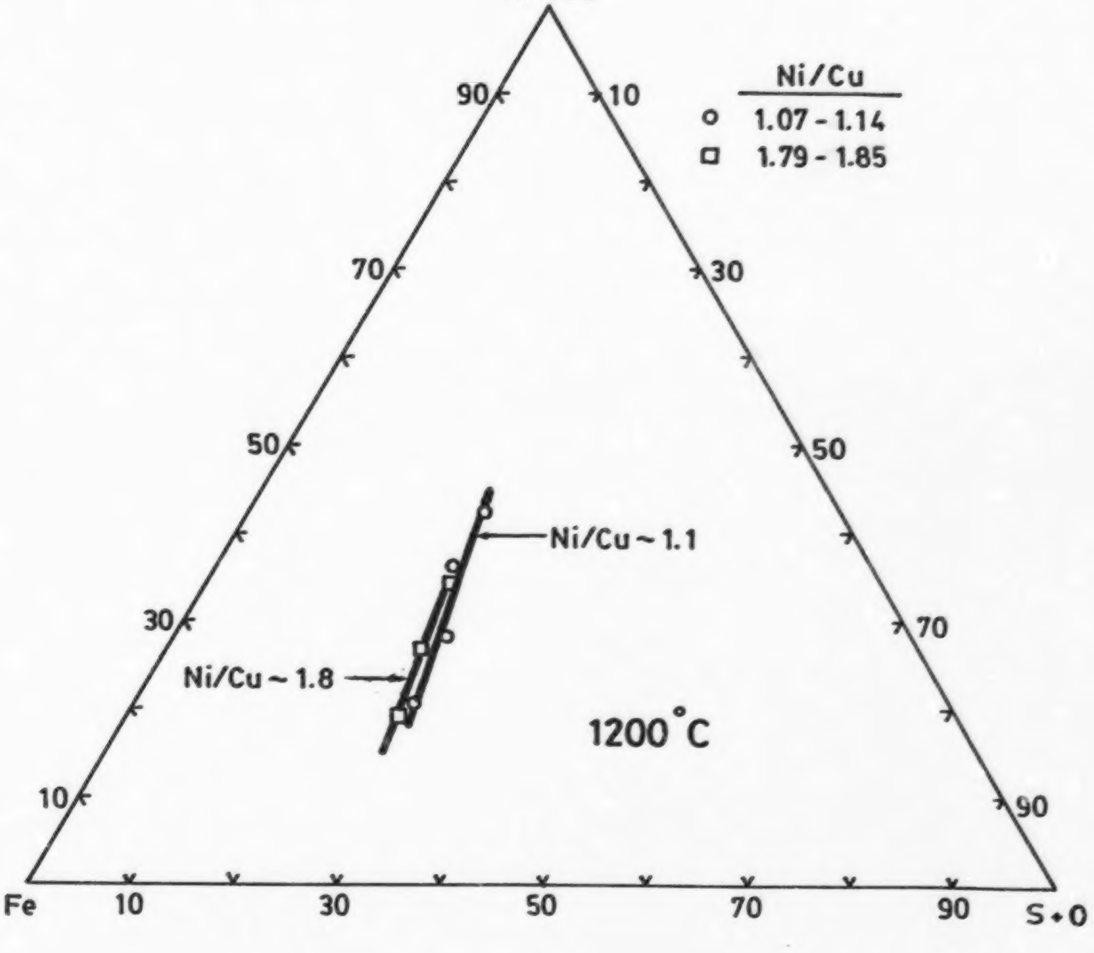

Figure 6. The Effect of the Ni/Cu Ratio on the Matte-Metal Saturation Boundary at 1200°C.

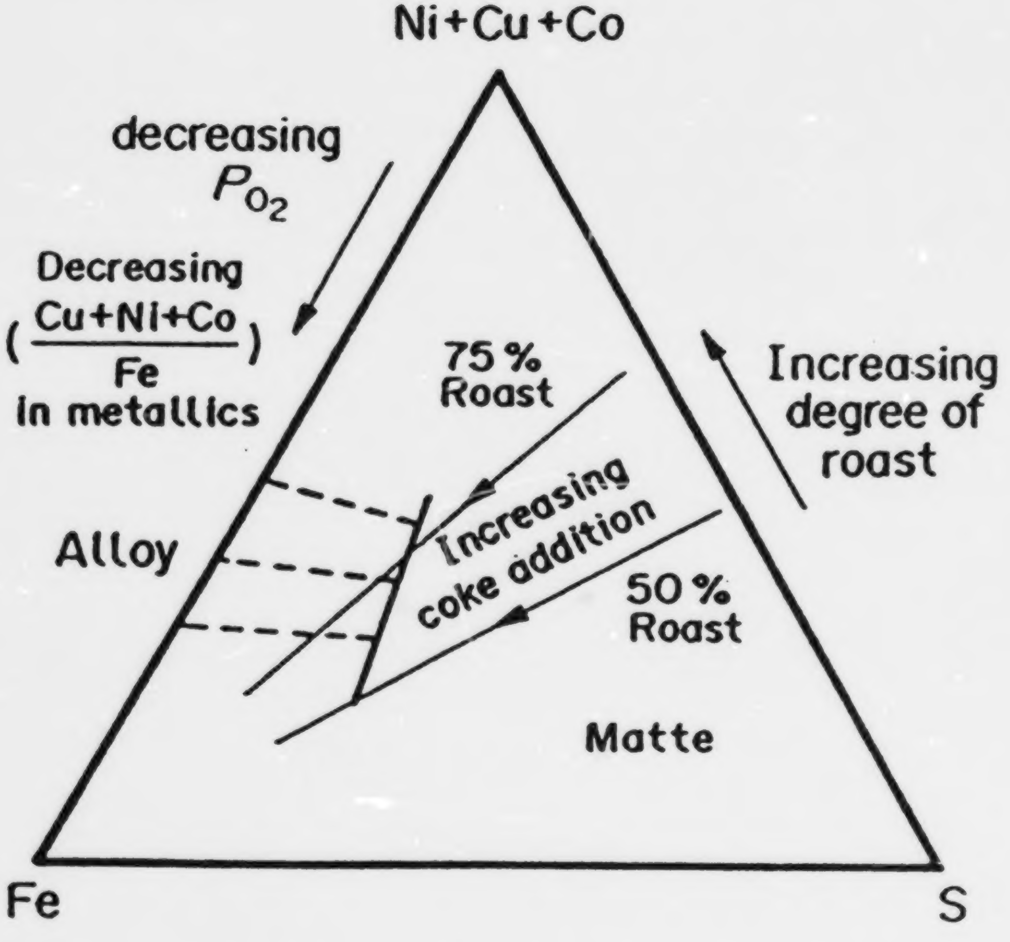
Ni+Cu+Co
decreasing P_{O_2}
Decreasing $\left(\frac{Cu+Ni+Co}{Fe}\right)$ in metallics
75% Roast
Increasing degree of roast
Increasing coke addition
Alloy
50% Roast
Matte
Fe
S

Figure 7. The Metallic Saturation Boundary in the Fe-S-(Ni+Cu+Co) System.

A high temperature conductivity apparatus was dismantled and transferred from Falconbridge to the University of Toronto. This equipment consists of a molybdenum crucible conductivity cell supported on a molybdenum pedestal. The pedestal extends to the furnace bottom and provides the electrical contact to the crucible. A molybdenum probe mounted to a precision movement device can be lowered down the center of the crucible into the molten slag sample. The cell resistance of the slag between the crucible and the probe is measured by applying a current with a frequency of 1000 cycles per second. Some of the parameters investigated include: temperature, Fe/SiO_2 ratio, lime content, and Fe_2O_3 additions to the slag. It was determined that increases in temperature and Fe/SiO_2, as well as additions of CaO and hematite all tend to increase the electrical conductivity of the slag. These results are presented graphically in Figures 8 and 9. The 'master slag' was obtained from Falconbridge Limited's electric furnaces.

These data are necessary in order to predict how the electric furnace will behave as the slag chemistry is altered. For example, it may be necessary to raise the temperature of the slag in order to control hearth buildups as more coke is added to the furnace. Also, it was determined in the first part of this contract that lime additions to the charge suppress the release of SO_2 during smelting. These additions cannot be made to the furnace without examining how they will affect furnace operation.

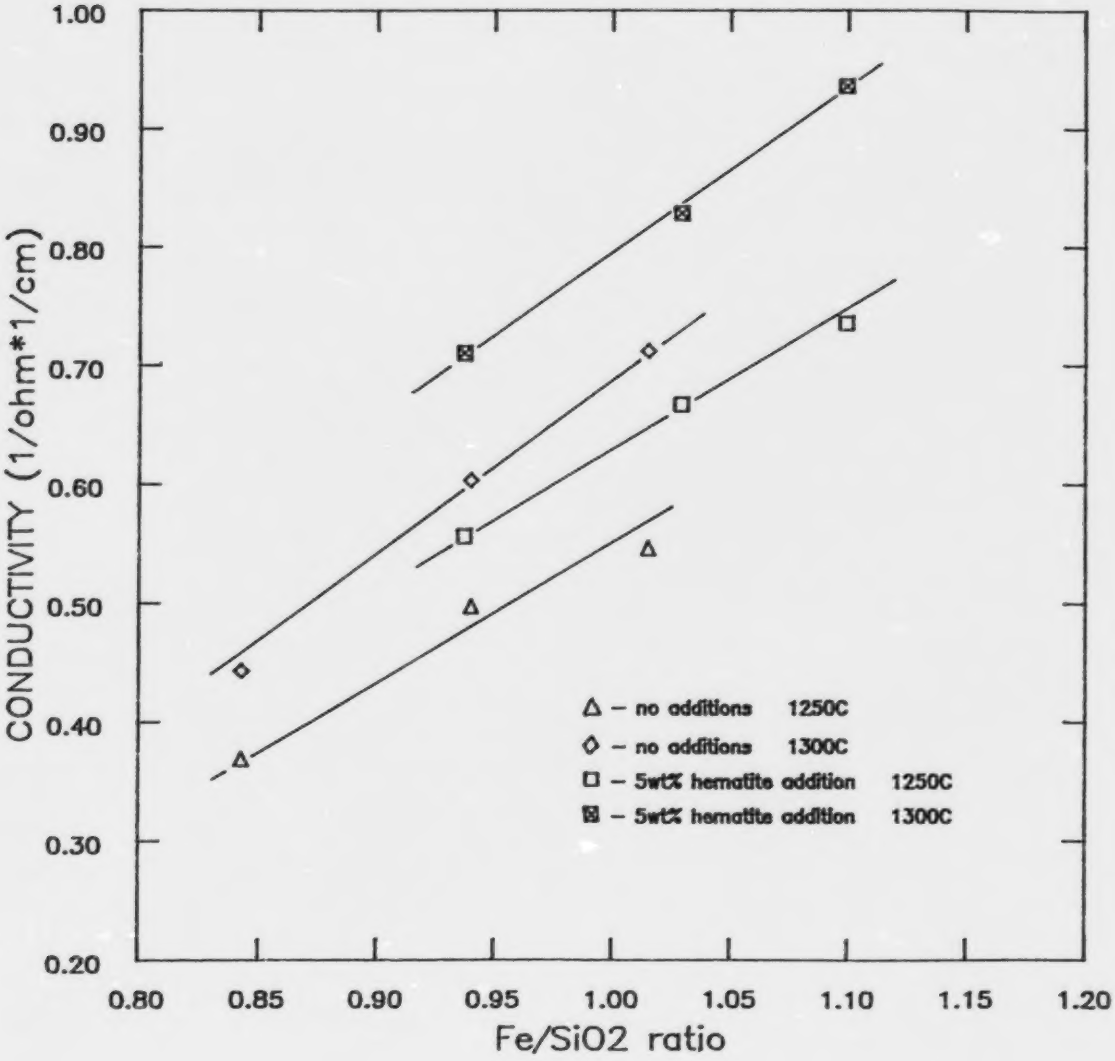

Figure 8. Effect of Fe/SiO_2 Ratio and Hematite Addition on Electrical Conductivity.

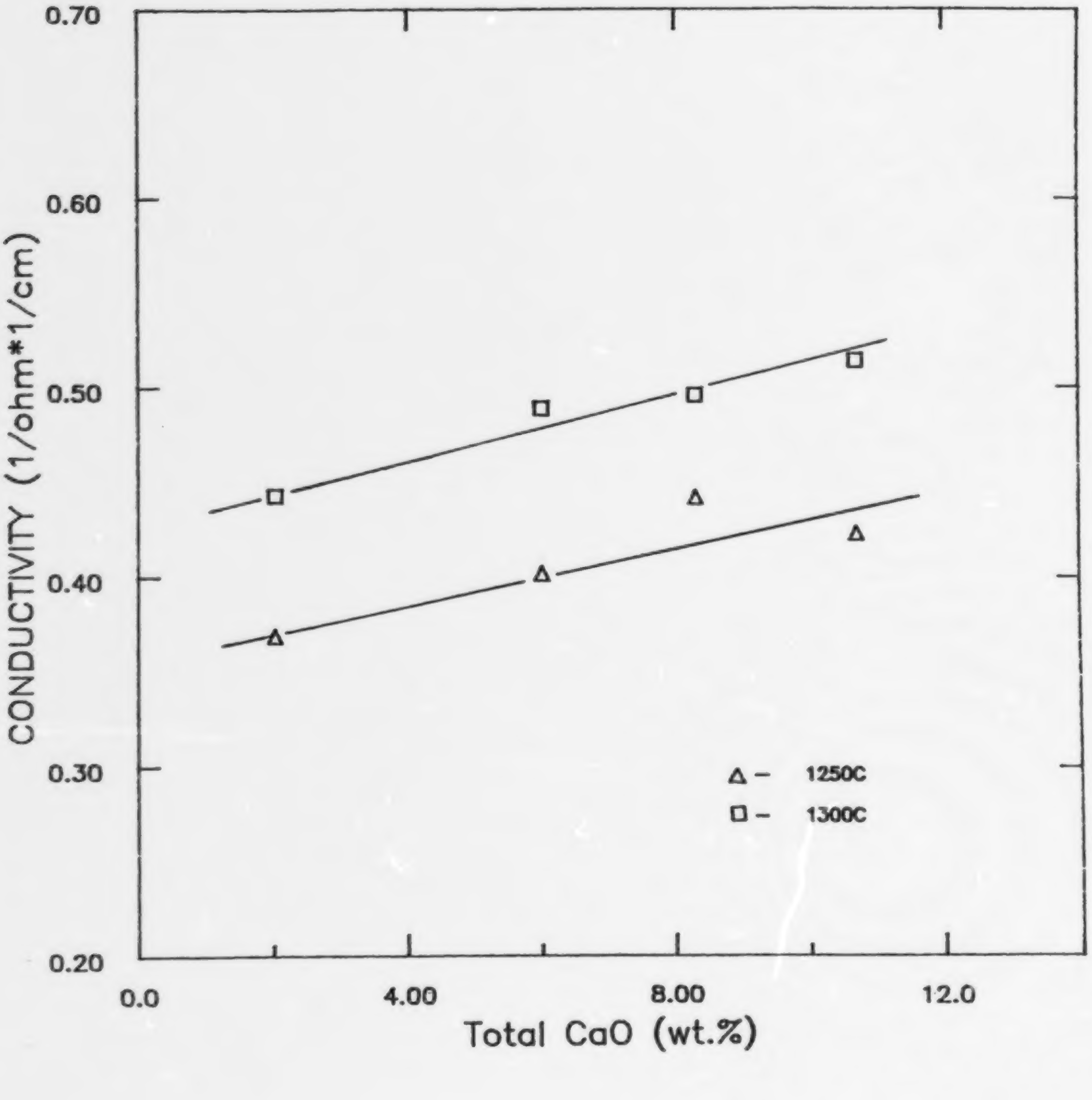

Figure 9. Effect of CaO Additions on Electrical Conductivity.

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